The Open University

The PHYSICAL WORLD

S207

Glossary

Introduction

The glossary terms for *The Physical World* are given below. Every emboldened term in the main text has an entry as well as some additional terms that have been included to increase completeness and aid usefulness. Words in *italics* are cross-referenced within this glossary. The reference following each entry (e.g. [*QPI*.3]) gives the book and chapter where the term is introduced. You will find that some terms occur in more than one book, and in some of these cases there may be subtle differences between the definitions given in different books. This is a consequence of the development of ideas as the course proceeds.

α- See *alpha*.

aberrations Distortions in optical images produced by the optical systems that form those images. Aberrations arise from a number of well-known causes and are classified accordingly. See, for example, *chromatic aberration* and *spherical aberration*. [*DFW*.3]

absolute temperature Any *temperature* measured on the *absolute temperature scale*. [*CPM*.1]

absolute temperature scale The *SI* scale of *temperature* measured in *kelvin* (K). On this scale, the lowest conceivable temperature, *absolute zero*, is 0 K, and the triple point temperature of H_2O is 273.16 K. (See also *temperature scale*.) [*CPM*.1]

absolute zero of temperature The lowest conceivable *temperature* for any *system*. It is represented by the value 0 K on the *absolute temperature scale*, and corresponds to a temperature of −273.15 °C on the Celsius temperature scale. In *classical physics*, where temperature is a measure of molecular agitation, absolute zero corresponds to all particles being at rest. [*CPM*.1]

absorption (and emission) of radiation General processes whereby *energy* carried by *electromagnetic radiation* may be added to, or taken from, the total energy of the system responsible for the emission or absorption. A particular case is that in which an *electron* makes a *radiative transition* between two *energy levels* in an atom. When an electron makes a transition from a lower energy level E_1 to a higher energy level E_2, the atom increases its total energy by an amount $E_2 - E_1$. In the case of a radiative transition, the atom obtains this energy by absorbing a single *photon* of energy $E_2 - E_1$. Similarly, an atom can emit a photon of energy $E_2 - E_1$ in a radiative transition when one of its electrons makes a transition from a higher energy level E_2 to a lower energy level E_1. [*QPI*.3]

acceleration The quantity that describes the (instantaneous) rate of change of *velocity* of a body. For a *particle* moving in one dimension along the *x-axis*, the acceleration a_x at any time is the instantaneous rate of change of the particle's velocity v_x, and is given by the *gradient* of the particle's *velocity–time* graph at the relevant time. This gradient is equal to the *derivative* of the velocity with respect to time at the relevant time, so the acceleration at time t may be written

$$a_x(t) = \frac{\mathrm{d}v_x(t)}{\mathrm{d}t}. \quad [DM.1]$$

Acceleration is a *vector* quantity, characterized by a *direction* as well as a *magnitude*. In one dimension the sign of a_x suffices to indicate the direction, but in two or three dimensions some other method must be used to indicate direction. This is often achieved by expressing the acceleration vector in terms of its (*Cartesian*) *components*, as in $\boldsymbol{a} = (a_x, a_y, a_z)$, where

$$\boldsymbol{a}(t) = \frac{\mathrm{d}\boldsymbol{v}(t)}{\mathrm{d}t}$$

and $\boldsymbol{v}(t)$ is the velocity vector. [*DM*.2]

acceleration due to gravity The *acceleration* of an object moving under the influence of gravity alone, close to the Earth's surface. It is directed vertically downwards and has an approximate *magnitude* of 9.81 m s^{-2}, which is conventionally given the symbol g. [*DM*.1; *PM*.1]

acceptors Impurity atoms added to a *semiconductor* to produce a *p-type* material. They have fewer *valence electrons* than are required for bonding and therefore absorb one or more electrons from the *valence band* of the semiconductor, creating *holes* there. In silicon, the acceptor atoms are often boron. [*QPM*.2]

accommodation The process whereby the eye adjusts its *focal length* so as to bring objects at different distances into sharp focus on the *retina*. [*DFW*.3]

1.4 PT/W

SUP 51244 0

action A term sometimes used to describe one of the forces in a *Newton's third-law* pair, the other member of the pair being referred to as a *reaction*. (Beware: action also has other technical meanings, quite different from that given here.) [*PM*.1]

action at a distance The notion that one body may influence another with which it is not in contact, without the aid of any intermediate agency such as an ether or a field. [*RU*.1]

addition rule for probabilities A rule stating that; if a number of alternative outcomes are mutually exclusive, the *probability* of getting one or other of these outcomes is found by adding their individual probabilities. [*CPM*.2]

additivity of mass The principle, in classical Newtonian physics, that the mass of a system is the sum of the masses of its constituent parts. (The development of *special relativity* has shown that this principle is not generally true, though it is still of considerable value and is widely used within *Newtonian mechanics*.) [*PM*.1]

adiabat A pathway on the *PVT surface* of a *system* (or on one of its projections, such as a *PV*-diagram) that corresponds to a *reversible adiabatic process*. [*CPM*.3]

adiabatic accessibility index The parameter A that appears in the *adiabatic condition* for an *ideal gas*, $PV^\gamma = A$, and which determines whether one *equilibrium state* can be reached from another by an *adiabatic process*. The adiabatic accessibility index is related to the *entropy* of the gas, and therefore has a constant value in any *reversible adiabatic process*. [*CPM*.3]

adiabatic inaccessibility The condition that exists between two *equilibrium states* of a system when it is impossible to go from one state to the other by any *adiabatic process*. [*CPM*.3]

adiabatic condition The condition $PV^\gamma = A$ that may be used to specify a particular *reversible adiabatic process* in a given quantity of *ideal gas* where the *ratio of heat capacities* is γ. The parameter A will have a constant value for any particular *reversible adiabatic process*, but will have different values for different reversible adiabatic processes that correspond to different values of the *entropy*. [*CPM*.3]

adiabatic process A process in which no *heat* is transferred. (See also *adiabatic condition*.) [*CPM*.3]

adiabatic system A *system* in a state of *thermal isolation*, so that no *heat* may be transferred to it or from it. [*CPM*.3]

aerodynamic drag A dissipative *force* arising from *air resistance* that opposes the motion of an object through air. For objects of moderate size and speed, moving through the atmosphere close to the Earth's surface, the magnitude of the aerodynamic drag is proportional to the square of the object's speed. For very small objects moving very slowly, the magnitude of the drag is proportional to the object's speed. [*PM*.1]

air resistance The phenomenon giving rise to *aerodynamic drag*, whereby the motion of an object through air is opposed. [*PM*.1]

allowed transition Any (*radiative*) *transition* corresponding to a change in *quantum numbers* that satisfies the relevant *selection rules*. For an electron in a spherically symmetric atom, these rules require that $\Delta l = \pm 1$ and $\Delta m_l = 0$ or ± 1. (Contrast with *forbidden transition*.) [*QPI*.3]

α-decay (alpha-decay) A type of radioactive *decay* in which a *nucleus* spontaneously emits an *α-particle*. [*QPM*.3]

α-particle (alpha-particle) A positively charged sub-atomic particle with about four times the mass of a hydrogen atom. Alpha-particles are composite particles consisting of two *protons* bound to two *neutrons*; they are identical to the nuclei of helium-4 atoms. Each α-particle has a mass of 4.0026 u and carries a positive charge of $2e$. [*PM*.3; *QPI*.1]

alternating current An *electric current* that periodically reverses direction as well as varying in magnitude. Such currents are frequently *sinusoidal* functions of time. (Contrast with *direct current*.) [*DFW*.1]

alternating current generator A device in which an externally supplied *torque* causes a coil of wire to rotate within a *magnetic field*, thus *inducing* an *electric current* in the coil that can be used to produce an *alternating current* in an external circuit. The alternating current is drawn off by means of two metal rings attached to either end of the coil, and connected via brushes to the external circuit. The way in which the current is drawn off distinguishes this device from a *direct current generator*. [*DFW*.1]

alternating current motor A device in which an externally supplied *alternating current* causes a coil of wire to rotate in a magnetic field. For example, if an alternating current is fed into an *alternating current generator*, then the *Lorentz force* acting on the conduction electrons in the coil of wire (which sits in a magnetic field) will cause the coil of wire to rotate about its axis. [*DFW*.1]

amorphous solid A *solid* in which the *atoms* exhibit *short-range order* but not *long-range order*. Such a solid is distinguished from a *liquid* by the fact that it is *rigid* rather than *fluid*. Materials such as glass can form such solids, even though they do not represent the lowest energy condition for the material. This is possible because the atoms in the material are not sufficiently mobile to allow it to make the transformation to the lower energy *crystalline solid*. [*CPM*.1; *QPM*.2]

ampere The *SI* unit of *electric current*, represented by the symbol A. The ampere is one of the seven SI *base units* and is defined by the following statement: When a steady current of one ampere flows in each of two straight, parallel, infinitely long, wires, set one metre apart in a vacuum, the *magnetic force* acting on each wire is of magnitude 2×10^{-7} N per metre of its length. [*SFP*.3; *SFP*.4]

amplitude (a) In the context of an *oscillation*; the amplitude is the *magnitude* of the maximum *displacement* of the oscillator from its *equilibrium position*. In the particular case of a *simple harmonic oscillator* described by the equation

$$x(t) = A\sin(\omega t + \phi)$$

the amplitude is represented by the parameter A. [*DM*.3]

(b) In the context of a *wave*; the amplitude is the maximum magnitude of the disturbance that constitutes

the wave (e.g. the displacement of a string from its equilibrium position). In the particular case of a simple travelling wave described by the equation

$$y(x,t) = A\sin(kx - \omega t + \phi)$$

the amplitude is represented by the parameter A. [*DFW*.2]

angle of incidence The acute angle (usually denoted i) between the *normal* to a surface and the direction of a specified ray that is incident upon the surface. [*DFW*.2]

angle of reflection The acute angle (usually denoted R) between the *normal* to a reflecting surface and the direction of a specified ray that has been reflected from the surface. [*DFW*.2]

angle of refraction The acute angle (usually denoted r) between the *normal* to a refracting interface and the direction of a specified ray that has been refracted at the interface. [*DFW*.2]

angular acceleration The (instantaneous) rate of change of *angular velocity*, $\mathrm{d}\boldsymbol{\omega}/\mathrm{d}t$. It is a *vector* quantity, sometimes represented by the symbol $\boldsymbol{\alpha}$, and its *SI* unit is the $\mathrm{rad\,s^{-2}}$. [*PM*.4]

angular coordinate A coordinate (usually denoted θ) that determines the *angular position* of a point in a (*plane*) *polar coordinate system*. [*DM*.3]

angular displacement A change in *angular position* in a specified sense, measured from a specified point. [*DM*.3]

angular frequency A characteristic property of an oscillating system, defined by the relation $\omega = 2\pi/T$, where T is the *period of oscillation* of the system. Since the *frequency* of an oscillator is defined by $f = 1/T$, it follows that $\omega = 2\pi f$. In the context of a *simple harmonic* oscillator, described by the equation $x = A\sin(\omega t + \phi)$, the angular frequency is represented by the parameter ω. The concept of angular frequency may be extended to the case of a wave, simply by taking T to be the *period* of the wave. Angular frequency is a positive scalar quantity with the *SI* unit $\mathrm{s^{-1}}$. (See also *angular wavenumber*.) [*DM*.3; *DFW*.2]

angular magnification The factor by which the apparent angular size of an object is increased when viewed through an optical system or instrument. It is defined by the equation $M = \alpha_{\mathrm{IM}}/\alpha_{\mathrm{OB}}$, where α_{IM} is the *visual angle* subtended at the eye by the image and α_{OB} is the maximum visual angle that can be subtended at the eye by the object (i.e. when the object is at the eye's *near point*). Also called the *magnifying power*. [*DFW*.3]

angular momentum The *momentum* associated with the *rotational motion* of a body. For a *particle*, the angular momentum $\boldsymbol{l}$, about a point O, is defined by the *vector product*

$$\boldsymbol{l} = \boldsymbol{r} \times \boldsymbol{p}$$

where $\boldsymbol{r}$ is the *displacement* of the particle from the point O, and $\boldsymbol{p}$ is the *linear momentum* of the particle. This implies that if the angle between $\boldsymbol{r}$ and $\boldsymbol{p}$ is θ, then $\boldsymbol{l}$ has magnitude $rp\sin\theta$, and points in a direction that is perpendicular to $\boldsymbol{r}$ and $\boldsymbol{p}$, as specified by the *right-hand rule*. The *SI* unit of angular momentum is the $\mathrm{kg\,m^2\,s^{-1}}$.

For an extended body, the angular momentum $\boldsymbol{L}$ about a given point depends on the way the body's mass is distributed, and on the components of its angular velocity $\boldsymbol{\omega}$. There are a number of important special cases in which the body is in uni-axial rotation about an axis of symmetry and $\boldsymbol{L} = I\boldsymbol{\omega}$, where I is the moment of inertia about that axis. However, $\boldsymbol{L} = I\boldsymbol{\omega}$ is *not* a general relation that will be true in all circumstances. (See *conservation of angular momentum*.) [*PM*.4]

angular position Expressed relative to a point O and an arbitrarily chosen straight line through O, the angular position θ of a point P is the angle (measured in the anticlockwise direction) from the chosen straight line to the line linking O to P. [*PM*.4]

angular speed The modulus of the rate of change of angular position of a particle or body:

$$\omega = \left|\frac{\mathrm{d}\theta}{\mathrm{d}t}\right|.$$

The angular speed of a body, about a point O represents the magnitude of its *angular velocity* about O. Angular speed is a positive scalar quantity with the *SI* unit $\mathrm{rad\,s^{-1}}$. [*DM*.3; *PM*.4]

angular velocity The angular velocity of a particle or body about a point O, is a *vector* quantity $\boldsymbol{\omega}$, with magnitude equal to the *angular speed* about O and directed along the (instantaneous) *axis of rotation* through O in the sense indicated by the *right-hand grip rule*.

If the displacement of a particle from O is $\boldsymbol{r}$, and if the velocity of that particle relative to O is $\boldsymbol{v}$, then the angular velocity $\boldsymbol{\omega}$ of that particle about the point O is related to $\boldsymbol{r}$ and $\boldsymbol{v}$ by the *vector product*

$$\boldsymbol{v} = \boldsymbol{\omega} \times \boldsymbol{r}$$

(Note that this result is *not* restricted to circular motion.)

In the case of a rotating *rigid body*, the angular velocity about every point fixed within the body has the same value at any given time. [*DM*.3; *PM*.4]

angular wavenumber A characteristic property of a wave defined by the relation $k = 2\pi/\lambda$, where λ is the *wavelength* of the *wave*. Angular wavenumber is a positive scalar quantity with the *SI* unit $\mathrm{m^{-1}}$. (See also *angular frequency* ω.) [*DFW*.2]

anode A positive *electrode*. In a vacuum electronic device (such as a cathode ray tube), the anode is given its charge by external means and therefore attracts electrons.

antibaryon The *antiparticle* of a *baryon*. [*QPM*.4]

antimatter Matter composed of antiparticles. The term may be applied to any quantity of matter from a single *antiparticle* to a collection of antiparticles, possibly even to antiatoms. [*QPM*.4]

antinode A fixed point in space at which the disturbance due to a *standing wave* (e.g. displacement of a string) attains its maximum value. (Contrast with *node*.) [*DFW*.2]

antiparticle Elementary particles that have the same mass and *spin* as certain known particles, but the opposite signs for other attributes, such as electric charge. For example, the *electron* and *positron* have the

same mass and both have *spin* $\frac{1}{2}$, but the former has a negative charge $-e$, while the latter has positive charge $+e$. [*QPM*.4]

antiquark The *antiparticle* of a *quark*. [*QPM*.2]

aperture That part of a *lens* through which light can be transmitted, or that part of a *mirror* from which light can be reflected. This may correspond to the full diameter of the lens (or mirror), or, if the lens is used with an adjacent *aperture stop* (as in a *camera*, for instance), to the effective diameter of the lens as limited by the stop. [*DFW*.3]

aperture diameter The 'effective' diameter of a *lens* (or *mirror*); it may be the actual diameter of the lens (or mirror) or, if the lens or mirror aperture is limited in some way (by an adjacent *aperture stop*, for instance), it would be the lesser diameter of the limited aperture. It is common (and convenient) to express the aperture diameter of a lens or mirror as a fraction of the *focal length* of that lens or mirror (e.g. $D = f/8$). The denominator of this fraction is known as the *F-number* of the lens (or mirror). Hence $D = f/F$ (which in the example above means that $F = 8$). [*DFW*.3]

aperture stop The (usually adjustable) iris diaphragm through whose central aperture light is admitted to the body of a *camera* or similar device. When it is adjustable, it can be used to alter the total *exposure* to which the film is subjected in a given time. [*DFW*.3]

aqueous humour A watery fluid in the human eye that fills the chamber between the *cornea* and the *crystalline lens*. It contributes substantially to the focusing power of the eyelens system: the cornea + aqueous humour combination acts as a fixed *focal length converging lens* with a *power* of about 40 *dioptres*. [*DFW*.3]

arbitrary constants Constants that arise in the *general solution* of a *differential equation* that are not present in the equation itself. The number of arbitrary constants in the general solution is equal to the *order* of the differential equation, and the values of the arbitrary constants are determined by the *initial conditions* that determine the details of the solution. [*PM*.1]

arc length The length of an arc, measured along the arc itself. [*DM*.3]

Archimedes' principle A principle asserting that; when a body is immersed, partly or wholly, in a *fluid*, its apparent weight is decreased by the weight of the fluid displaced. [*CPM*.4]

argument The *independent variable* that actually determines the value of a function, e.g. θ is the argument of $\sin\theta$, and 2θ is the argument of $\sin(2\theta)$. [*DM*.3]

astronomical unit A unit of distance, equal to the mean distance between the Earth and the Sun. The astronomical unit is represented by the symbol AU, and its value is given by $1\,\text{AU} = 1.49598 \times 10^{11}\,\text{m}$. [*PM*.5]

asymmetry effect An effect that influences the properties of *nuclei*, including their masses, and which arises from the fact that the *strong nuclear force* is slightly stronger between pairs of unlike *nucleons* than between pairs of like nucleons. (In other words, it is slightly stronger between a *neutron* and a *proton* than it is between two neutrons or between two protons.) [*QPM*.3]

atom The smallest electrically neutral sample of an *element* that retains the fundamental chemical and physical identity of that element. [*CPM*.1]

atomic mass unit A unit of mass, denoted u or amu, and defined as one-twelfth of the mass of one *atom* of carbon-12, the most common *isotope* of carbon. $1\,\text{u} = 1.6605 \times 10^{-27}\,\text{kg}$. [*CPM*.1]

atomic number The number of *protons* in a specified *nucleus*. The atomic number is usually represented by the symbol Z, and is equal to the difference between the *mass number* A and the *neutron number* N, so $Z = A - N$. All atoms of the same *element* have the same atomic number. The positive charge on the nucleus is Ze. For a neutral atom, Z is also equal to the number of electrons in the atom. [*CPM*.1; *QPI*.1; *QPI*.3; *QPM*.3]

aurora A luminous atmospheric phenomenon, observed in high latitudes. It arises from *plasma* particles from the *solar wind* which become trapped in the Earth's *magnetic field* and oscillate between the magnetic North and South Poles. Near the poles these charged particles excite the oxygen and nitrogen molecules in the upper atmosphere causing them to emit light seen as the beautiful auroral display. [*SFP*.4]

average value The typical or representative value of a quantity that may, in principle, have any one of a range of values. The term average value may be taken to mean the *predicted average value* or the *measured average value*, depending on context. [*CPM*.2]

average velocity A *vector* quantity that measures the net rate of change of a particle's position over a given time interval. If the particle undergoes a *displacement* $\Delta\boldsymbol{r}$ in a time interval Δt, then the average velocity over that time interval is defined to be

$$\langle \boldsymbol{v} \rangle = \frac{\Delta\boldsymbol{r}}{\Delta t}. \quad [DM.2]$$

Avogadro's constant The number of basic particles (*atoms*, *molecules*, *ions*, etc.) per *mole* of any substance, $N_m = 6.022 \times 10^{23}\,\text{mol}^{-1}$. This is equal to *Avogadro's number* per mole. [*CPM*.1]

Avogadro's hypothesis The conjecture, now well established, that; equal volumes of different *gases*, at the same *temperature* and *pressure*, contain the same number of *molecules*. [*CPM*.1]

Avogadro's number The number of basic particles (*atoms*, *molecules*, *ions*, etc.) in one *mole* of any substance. Avogadro's number is equal to the number of atoms in $12 \times 10^{-3}\,\text{kg}$ of the carbon *isotope* carbon-12 (6.022×10^{23}). [*CPM*.1]

axis A *straight line* along which the values of a position coordinate may be measured. [*DM*.1]

axis of rotation A line that remains at rest in a specified rotation. [*PM*.4]

β- See *beta*.

back EMF The *EMF* that arises in an *electric motor* or similar device as the motor starts to turn, and which opposes the externally supplied EMF that is responsible for that turning. Since an electric motor is constructed like an *electric generator*, any movement of its coil will produce an *induced EMF* which opposes the change that caused it (by *Lenz's law*). This is the back EMF, which must act in the opposite direction to the applied EMF

from the battery or power supply that caused the coil to move. [*DFW*.1]

Balmer's formula The empirical formula

$$\lambda_n = 364.56\left\{\frac{n^2}{n^2-4}\right\}\text{nm}$$

giving the wavelengths of the spectral lines of the *Balmer series* which includes the visible lines in the spectrum of atomic hydrogen. [*QPI*.1]

Balmer series A series of lines in the spectrum of atomic hydrogen, the visible members of which have wavelengths 656.210 nm, 486.074 nm, 434.010 nm and 410.12 nm. In the context of the *Bohr model* of the atom, these lines correspond to *transitions* to the $n = 2$ *Bohr orbit* from orbits with $n = 3$, 4, 5 and 6, respectively. Transitions from orbits with higher values of n correspond to lines that are in the ultraviolet part of the spectrum. [*QPI*.1]

band theory of solids A theory that accounts for the existence of *semiconductors*, *insulators* and *metals* on the basis of the *quantum-mechanical* behaviour of *electrons* confined by spatially periodic *potential energy* functions. The theory implies that the *energy levels* of electrons in a *crystalline solid* are distributed in a number of bands that may overlap or be separated by energy gaps of various sizes. The theory provides the foundation for solid state electronics. (See also *nearly-free electron model*, and *tight-binding model*.) [*QPM*.2]

barn A unit of *cross-section* for particle collisions. It is represented by the symbol b and is defined by the relation $1\,\text{b} = 10^{-28}\,\text{m}^2$. [*QPM*.4]

barometric formula The formula

$$P(z) = P(0)\exp(-z/\lambda)$$

that relates pressure P to altitude z in a *thin isothermal atmosphere*, where the *scale height* is λ. [*CPM*.4]

baryon A term used to describe *strongly interacting* particles that have half odd-integer *spin* (i.e. spin $\frac{1}{2}$, $\frac{3}{2}$, etc.). Each baryon is a combination of three *quarks*, and consequently has *baryon number* $B = 1$. Baryons are a sub-class of *hadrons*. [*QPM*.4]

baryon number A dimensionless quantity, usually represented by the symbol B, that is conserved in all known interactions. All *baryons* have $B = 1$, and all *antibaryons* have $B = -1$. All *quarks* have $B = 1/3$, and all *antiquarks* have $B = -1/3$. [*QPM*.4]

base unit Any one of the seven *SI* units that provide the basis for the definition of all the other (derived) SI units. The seven base units are; *metre* (m), *kilogram* (kg), *second* (s), *mole* (mol), *kelvin* (K), *ampere* (A) and candela (Cd). [*DM.1*]

battery A device for producing an *electromotive force* and thus supplying *electric current*. It consists of two or more electrical *cells* connected together. [*SFP*.3]

BCS theory The theory by Bardeen, Cooper and Schrieffer which, in 1957, gave a quantum-mechanical explanation of *superconductivity* by considering the formation of *Cooper pairs* and the development of the *superconducting energy gap* at low temperature. [*QPM*.2]

Bell's inequality An inequality satisfied by a certain combination of spin component correlation functions according to any theory that exhibits both *locality* and *realism*. Quantum mechanics predicts that the Bell inequality will be violated and experiments indicate that this is the case. (See also *Bell's theorem*.) [*QPI*.4]

Bell's theorem Based on the fact that quantum mechanics predicts that *Bell's inequality* will be violated, Bell's theorem asserts that: any theory which exhibits both *locality* and *realism* cannot replicate all the predictions of quantum mechanics. [*QPI*.4]

Bernoulli's equation The equation

$$P + \rho v^2/2 + \rho g h = \text{constant}$$

that describes the law of conservation of energy in an *ideal fluid* of density ρ. It relates *pressure* P, speed v and height h, at different points along a *streamline*. [*CPM*.4]

Bernoulli's principle A principle asserting that; at constant height, the speed of flow of an *ideal fluid* is greatest where the *pressure* is smallest, and *vice versa*. It is quantified by *Bernoulli's equation*. [*CPM*.4]

β-decay (beta-decay) A type of radioactive *decay* process. There are three distinct kinds of decay processes that are classed as β-decay. In negative beta-decay (*β^--decay*) the *nucleus* spontaneously emits an *electron* and an antineutrino. In positive beta-decay (*β^+-decay*), also called *positron decay*, the nucleus spontaneously emits a *positron* and a *neutrino*. In *electron capture* the nucleus spontaneously captures an orbiting electron in an s state (quantum number $l = 0$) and emits a neutrino; an X-ray is also emitted as electrons in outer shells fall into the vacancy left by the capture. [*QPM*.3]

β^+-decay See *β-decay*. [*QPM*.3]

β^--decay See *β-decay*. [*QPM*.3]

β-particle (beta-particle) Another name for an energetic *electron* emitted by the nucleus. [*QPM*.4]

bifocal spectacles Spectacles in which the top part of each '*lens*' has a different *focal length* to the bottom part, thereby enabling a prescription for both close viewing and distant vision to be incorporated into the one pair of spectacles. They are often required by people as they get older and begin to suffer from *presbyopia*. [*DFW*.3]

binding energy The least amount of *energy* needed to separate a system into its (appropriately specified) components. For example, in the case of a *nucleus*, the binding energy is the energy required to separate the individual *protons* and *neutrons* that comprise the nucleus. (The binding energy is therefore equal to the energy that would be released if the nucleus were to be assembled from its separated constituents.) [*CPM*.1; *QPM*.3]

binding energy per nucleon The amount of *energy*, obtained by dividing the *binding energy* B of a specified nucleus by the *mass number* A of that nucleus. The binding energy per nucleon provides a measure of the stability of a nucleus relative to other nuclei. A larger value of B/A indicates a more stable nucleus. [*QPM*.3]

blackbody An ideal absorber of *electromagnetic radiation* that would absorb all the radiation that was incident upon it. Such a body would also be an ideal emitter, and would emit electromagnetic radiation with a *spectrum* that depended only on the *temperature* of the body. (See *blackbody radiation*.)

blackbody radiation *Electromagnetic radiation* that is in *thermal equilibrium* with matter at a fixed *temperature*. Its name derives from the fact that its spectrum is identical to that which would be emitted by a *blackbody* at the same temperature. Blackbody radiation is also called *thermal radiation* or *cavity radiation*. It consists of a gas of *photons* with a range of energies described by *Planck's radiation law*. [*QPI*.1; *QPM*.1]

blackbody spectrum The spectrum (intensity of radiation in a small wavelength range $\Delta\lambda$ at each wavelength λ) emitted by a *blackbody*. [*QPI*.1]

black hole A region of space from which light is unable to escape due to the action of gravity. When a star has exhausted all its internal sources of energy, it will collapse under its own gravitational attraction. If the mass of the residual stellar core is greater than about three times the mass of the Sun, it will eventually become so concentrated that the *escape speed* from its surface will exceed the speed of light. In this state, according to classical physics no radiation (or matter) can escape from it, so the collapsing core will inevitably lead to the formation of a black hole. [*SFP*.2]

blind spot The small region at the back of the eye, within the area of the *retina*, where the *optic nerve* enters. Any light falling on this spot will be undetected. [*DFW*.3]

bob A heavy weight attached to the lower end of a *pendulum* or oscillator. [*DM*.3]

Bohm's theory A theory that replicates all the predictions of *quantum mechanics*, but does so at the price of introducing a highly non-local 'quantum potential'. It is related to de Broglie's theory, in which the *wavefunction* was supposed to act as a 'pilot wave', influencing the (classical) motion of particles and guiding them towards the destinations that quantum mechanics predicted. (Bohm's theory may be regarded as a *realist interpretation* of quantum mechanics, in which case it is known as the *ontological interpretation*.) [*QPI*.4]

Bohr model A semi-classical model of the atom introduced by Niels Bohr in 1913. The model assumes (classically) that a central, positively charged, *nucleus* is orbited by one or more *electrons* that are held in place by *electrostatic forces*. It also assumes (non-classically) that the electrons are confined to *Bohr orbits* in which the *angular momentum* is an integer multiple of $\hbar$ (Planck's constant divided by 2π). It further assumes that the electrons do not emit *electromagnetic radiation* as long as they remain in one of the allowed orbits, but that emission (or absorption) does occur when an electron makes a *transition* that takes it from one orbit to another. [*QPI*.1]

Bohr orbit Any of the circular paths that an electron is allowed to follow as it orbits a nucleus, according to the *Bohr model* of the atom. In the case of the hydrogen atom, each value of the Bohr quantum number n corresponds to an orbit in which the magnitude of the angular momentum is $L = n\hbar$. The radius of such an orbit is $r_n = n^2a_0$, and the speed of the electron is $v_n = e^2/2\hbar\varepsilon_0 n$. Here, $\hbar$ is Planck's constant divided by 2π and a_0 is the *Bohr radius*. [*QPI*.1]

Bohr radius The radius of the lowest orbit in the *Bohr model* of the hydrogen atom:

$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{m_e e^2} = 0.53 \times 10^{-10}\,\mathrm{m}$$

where m_e and e are the mass of the electron and the magnitude of the charge on the electron, respectively, and $\hbar$ is Planck's constant divided by 2π. [*QPI*.1]

Bohr's equation The formula derived by Bohr, using his model of the hydrogen atom, which gives the *wavelength* of any *spectral line* in the hydrogen atom, due to the electron making a *transition* from an orbit characterized by the quantum number n to a lower orbit characterized by the quantum number q, namely

$$\lambda_{n\to q} = 91.127\left\{\frac{q^2n^2}{n^2-q^2}\right\}\mathrm{nm}.$$

When q is put equal to 2, Bohr's equation reduces to *Balmer's formula*. [*QPI*.1]

Boltzmann factor The factor $e^{-E/kT}$ that appears in *Boltzmann's distribution law* and in the *Boltzmann occupation factor*. [*CPM*.2; *QPM*.1]

Boltzmann occupation factor The factor $NAe^{-E/kT}$ that determines the average number of particles occupying a quantum state of energy E in a system of N distinguishable particles in *thermal equilibrium* at *absolute temperature* T. The parameter A is a *normalization factor*, and k is *Boltzmann's constant*. [*QPM*.1]

Boltzmann's constant This is $k = 1.381 \times 10^{-23}\,\mathrm{J\,K^{-1}}$, the constant that relates *temperatures* to characteristic *energies*. In classical physics, the average *translational energy* of a molecule in a gas that is in thermal equilibrium at (absolute) temperature T is given by $3kT/2$. [*CPM*.1]

Boltzmann's distribution law A law stating that; for a (classical) *gas* in *thermal equilibrium* at *absolute temperature* T, the *probability* of finding a given *molecule* in a given *phase cell* of energy E is $p = Ae^{-E/kT}$, where A has the same value for all phase cells, no matter what their energy. [*CPM*.2]

Boltzmann's equation The equation $S = k \log_e W$, that relates the *entropy* S of a given *equilibrium state* of a *macroscopic system* to the number W of *configurations* that correspond to that equilibrium state. The constant k is *Boltzmann's constant*. [*CPM*.3]

Boltzmann's principles of statistical mechanics Two principles, formulated by Ludwig Boltzmann at the foundation of *statistical mechanics*. The principles assert that:

1 The only allowed *configurations* are those with fixed energy, E.

2 Each of the allowed configurations are equally likely. [*CPM*.2]

Boltzmann's statement of the second law of thermodynamics The statement that; the *entropy* of the *Universe* tends to a maximum. [*CPM*.3]

bonding The phenomenon whereby atoms are bound together to form molecules or solids. There are several different kinds of bonding though all are essentially manifestations of the electrical interaction between charged particles. For further details see *covalent bond*, *ionic bond*, *mixed bonding*, *hydrogen bonding*, *metallic solid* and *van der Waals forces*.

bond directionality A phenomenon associated with the *covalent bond* between atoms (but not with *ionic* or *metallic* bonds) whereby the resulting molecules have a definite geometric structure. This arises because the paired *valence electrons* that form the covalent bonds are not free to move away from the bonded atoms but are strongly attached to them. This becomes apparent when one atom is bonded to two or three others and there are definite angles between the bonds. [*QPM*.2]

bond saturation A phenomenon associated with the *covalent bond* that limits the number of atoms that may be directly bonded to any selected atom. This arises because the pairing of all *unpaired electrons* in the selected atom prevents the formation of any additional *covalent bonds*. [*QPM*.2]

Born interpretation The suggestion, first explicitly advanced by Max Born, that in *quantum mechanics* the *wavefunction* of a particle determines the *probability* of finding the particle in a given region. For example, if the particle is confined to the x-axis and is described by the normalized *time-independent wavefunction* $\psi(x)$, then the probability of finding it in the small region between x and $x + \Delta x$ is

$$P = |\psi(x)|^2 \Delta x.$$

Similarly, in three dimensions, the probability of finding the particle in a given small region of volume ΔV, centred on the point $\boldsymbol{r}$, is

$$P = |\psi(\boldsymbol{r})|^2 \Delta V.$$

In the context of *de Broglie waves*, Born's interpretation may be taken to imply that the probability of finding a particle in a given small region is proportional to the square of the amplitude of the particle's de Broglie wave in that region. This justifies the interpretation of de Broglie waves as *probability waves*. [*QPI*.4]

Bose–Einstein condensate A phase of matter, for a macroscopic system of identical *bosons* at very low temperature, in which a large number of the particles occupy the same *translational quantum state*. The condensation occurs abruptly at a characteristic temperature. [*QPM*.1]

Bose occupation factor The factor

$$F_{\rm B}(E) = \frac{1}{e^{(E-\mu)/kT} - 1}.$$

that determines the average number of particles occupying a quantum state of energy E in a system of indistinguishable *bosons* in *thermal equilibrium* at *absolute temperature* T. For *photons*, the characteristic energy μ is 0. [*QPM*.1]

boson A particle with integer or zero *spin* (i.e. spin 0, 1, 2, etc.). Bosons do not obey *Pauli's exclusion principle*. Consequently, any number of bosons may occupy any given quantum state. [*QPM*.1; *QPM*.4]

bottom A dimensionless quantity that is conserved in *strong* and *electromagnetic interactions*, but not in *weak interactions*. See *bottom quark*. [*QPM*.4]

bottom quark One of the six types of *quark*. It is the only quark to have non-zero *bottom* (or bottomness). [*QPM*.4]

bound particle A particle that is trapped in a *potential well* because its total energy is less than its potential energy at every point on the boundary of the well. In *classical physics*, a bound particle is rigorously confined to the region in which the potential energy is less than the total energy. In *quantum mechanics*, *tunnelling* can occur, and the particle can stray beyond the classically allowed region; nevertheless, the *wavefunction* of the particle usually decreases rapidly beyond the classically allowed region, so the probability of tunnelling is generally quite small. In quantum mechanics, the *energy levels* of a bound particle are discrete. [*QPI*.2]

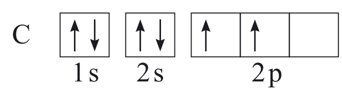
boundary conditions (of a wave) Conditions that constrain a wave by specifying its behaviour at its end points. In the case of a *standing wave* the boundary conditions restrict the possible wavelengths and thereby limit the allowed frequencies. [*DFW*.2]

boundary layer The layer of *fluid* next to a solid surface that remains dominated by viscous effects, no matter how large the *Reynolds number*, Re, may be. For Reynolds numbers much greater than 1, the thickness of this layer is proportional to $1/\sqrt{Re}$. The boundary layer is the region in which the fluid velocity makes an abrupt transition from the value found in the external flow to the value of zero (relative to the solid surface) required by the *no-slip condition*. Eddies and whirlpools tend to form within the boundary layer. [*CPM*.4]

boundary layer separation The phenomenon whereby the *boundary layer* of a fluid becomes detached from the solid surface around which it forms. [*CPM*.4]

Boyle's law A law stating that; at constant *temperature*, the *pressure* of a fixed mass of an *ideal gas* is inversely proportional to its volume. [*CPM*.1]

box notation One of the two common ways of writing down the electronic configuration of an atom (the other being *standard notation*). In box notation, a small box is shown for each combination of the *quantum numbers n*, l and m_l. The *spin magnetic quantum number* m_s of any occupying electron is indicated by an upward or downward pointing arrow depending on whether $m_s = +\frac{1}{2}$ or $-\frac{1}{2}$. If a box contains both upward and downward arrows, both spin states for that combination of n, l and m_l are occupied. For example, the *ground state* of carbon is written in the box notation as



[*QPI*.3]

Bragg's law A law stating that; a beam of *X-rays* can be reflected from parallel planes of *atoms* in a *crystal* when

$$n\lambda = 2d \sin\theta$$

where n is an integer (the *order* of the reflection), λ is the X-ray *wavelength*, θ is the angle between the beam

direction and the normal to the atomic planes, and *d* is the separation of atomic planes in the crystal. [*QPM*.2]

brittle fracture The phenomenon, exhibited by some materials, where the application of a stress leads to a sudden failure of the material with little or no plastic deformation. Many real materials contain tiny cracks, either within the bulk or on the surface, which can act as a source of weakness. Stress is concentrated at the ends of these cracks, stretching them open. If a crack is large enough, even a small additional stress can cause the crack to suddenly and catastrophically extend right across the sample, creating brittle failure. Brittle fracture typically occurs in materials that are not *ductile* and which have a large covalent component to their *bonding*. [*QPM*.2]

Brownian motion The microscopic random motion exhibited by small particles suspended in *gases* or *liquids*. Einstein recognized that Brownian motion is a result of the incessant bombardment of the observed particle by *molecules* in the surrounding *fluid*. [*CPM*.1]

bubble chamber A device for detecting *elementary particles*, based on observing the trails of tiny bubbles left by charged particles as they pass through a superheated liquid (i.e. a liquid that is temporarily above its boiling temperature). [*QPM*.4]

calculus The branch of mathematics concerned with the way in which small changes in one quantity determine, or are determined by, changes in related quantities. [*DM*.1]

calorie An obsolescent unit of energy, mostly associated with *thermal energy*, and equal to 4.186 J. The 'Calorie' (note the upper case C) sometimes referred to in nutritional information, is equal to 1000 calories. [*CPM*.3]

camera A device for recording optical images on film. Its principal components are a *lens*, a timing *shutter*, an adjustable *aperture stop*, and some form of *film* transport mechanism. With the advance of digital electronics, an increasing number of cameras are being designed to focus their image onto a photosensitive electronic detector array, which then enables the optical pattern information to be digitized and stored in a form readable by a computer. [*DFW*.3]

capacitance The quantity that describes the ability of a conductor or a system of conductors to store charge by altering its electrostatic potential relative to some agreed reference point. In the case of a two-plate *capacitor* the capacitance is the ratio of the *charge q* on one of the plates to the *potential difference V* between that plate and the other plate: $C = q/V$. The capacitance of a given capacitor is determined by the geometry and composition of the device and is independent of q and V. Thus, in the case of the parallel plate capacitor again, the capacitance is $\varepsilon_r\varepsilon_0 A/d$, where A is the area of the plates, d is their separation, ε_0 is the *permittivity of free space* and ε_r is the *relative permittivity* of the medium between them. The *SI* unit of capacitance is the *farad*, represented by the symbol F, where

$$1\,\mathrm{F} = 1\,\mathrm{C\,V^{-1}}.$$ [*SFP*.2]

capacitive circuit An electrical circuit containing a capacitor. When an *alternating current* is applied to the circuit, the *phase* of the voltage across a capacitor lags the phase of the current through it by one-quarter of a cycle. [*DFW*.1]

capacitor An element in an electric circuit whose primary function is to separate *charge* and hence store energy. A *parallel plate capacitor* consists of two conducting plates, usually separated by an insulating medium of high *relative permittivity*. Any capacitor will have a certain value of *capacitance*. When a sinusoidally alternating current passes through a capacitor, the sinusoidally varying *voltage* across the capacitor lags the sinusoidally varying current by a quarter of a period. [*SFP*.2]

Carathéodory's statement of the second law of thermodynamics The statement that; in the neighbourhood of any *equilibrium state* of a *macroscopic system*, there are states that are *adiabatically inaccessible*. [*CPM*.3]

carbon dating A method of dating pieces of organic archaeological or fossil material by measuring the amount of radioactive ^{14}C present in the material. It is assumed that the ^{14}C was taken in by the material from the atmosphere when it was part of a living organism and has since undergone radioactive *decay* according to the *exponential decay law*. [*QPM*.3]

Carnot cycle A *reversible cyclic process* involving a fixed quantity of *ideal gas*, and consisting of two *isothermal processes* linked by two *adiabatic processes*. [*CPM*.3]

Carnot engine An 'ideal' *heat engine*, the operation of which is based on a *Carnot cycle*. A Carnot engine converts heat to work with the greatest efficiency possible for any heat engine. [*CPM*.3]

Carnot refrigerator An 'ideal' *refrigerator*, the operation of which is based on a (reversed) *Carnot cycle*. [*CPM*.3]

Cartesian components The *scalar* quantities required to specify a *vector* relative to a *Cartesian coordinate system*. For example, a vector $\boldsymbol{v}$ may be specified relative to a three-dimensional Cartesian coordinate system, with axes x, y and z, by determining the projection of $\boldsymbol{v}$ in the x-, y- and z- directions. These projections are the Cartesian components v_x, v_y, and v_z, and we can write $\boldsymbol{v} = (v_x, v_y, v_z)$. The term 'Cartesian components' is often abbreviated to 'components'. [*DM*.2]

Cartesian coordinate system A system of mutually perpendicular *axes*, meeting at a single point called the *origin*, and calibrated in a common way (usually in metres, starting from zero at the origin), that allows the *position* of any point to be uniquely specified by an *ordered set* of values. In three-dimensional space, three axes are required; these are conventionally labelled x, y and z; and the coordinates of a point P are represented by the ordered triplet of *position coordinates* (x_P, y_P, z_P). Three-dimensional Cartesian coordinate systems may be *right-handed* or left-handed. It is conventional to use right-handed systems for most purposes. [*DM*.2; *DM*.3]

cascade particle See *xi particle*. [*QPM*.2]

Cassegrainian telescope A *reflecting telescope* using a *converging mirror* (the *objective* or *primary mirror*) and a small *diverging mirror* (the *secondary mirror*). This secondary mirror increases the *effective focal*

length of the telescope, and directs the light rays back through a hole in the centre of the primary mirror. An *eyepiece lens* may be positioned to view the *virtual image* directly by eye; alternatively a photographic or electronic detector may be used to capture a *real image*. (See also *telescope*.) [*DFW*.3]

cathode A negative *electrode*. In a vacuum electronic device (such as a cathode ray tube) electrons are emitted from the cathode and attracted to the anode.

causality The principle that a cause should always precede its effect. *Special relativity* preserves this logical relationship, provided it is assumed that the *speed of light* in a vacuum is the maximum speed at which a signal can travel. [*DFW*.4]

cavity radiation See *blackbody radiation*. [*QPM*.1]

cell A single unit of a *battery*. It consists of a pair of metal plates immersed in an *electrolyte*. An *electric current* is produced by chemical interaction between the plates and the electrolyte. [*SFP*.3]

central problem of relativity The problem of determining the *coordinate transformation* that links two *inertial frames of reference* in *standard configuration*. The solution is the *Lorentz transformation*. [*DFW*.4]

centre of curvature (of a spherical mirror) The point that lies at the centre of the sphere of which the surface of the spherical mirror forms a part. [*DFW*.3]

centre of mass The unique point associated with any given *rigid body* (which does not necessarily lie within the body) with the property that if any unbalanced force acting on the body has a *line of action* that passes through the centre of mass, then the only effect of that force will be to cause *translational acceleration* of the body. If the total *external force* acting on a body is $\boldsymbol{F}$, the acceleration of the centre of mass is $\boldsymbol{a} = \boldsymbol{F}/m$, where m is the total mass of the body. So, if the body experiences no net external force (e.g. if it is isolated), its centre of mass moves with constant velocity. The centre of mass can therefore be regarded as the point at which Newton's laws for particle motion can most easily be applied to rigid bodies. [*PM*.1]

centrifugal force A *fictitious force* that may be used to account for certain aspects of the motion of bodies observed from a rotating (non-inertial) *frame of reference*. The effect of the centrifugal force is to cause bodies to accelerate radially outwards from the *axis of rotation*. By introducing such fictitious forces, the motion of the bodies may be made to conform with the predictions of Newton's laws, which do not, strictly speaking, apply in such frames. (See also *Coriolis force*.) [*PM*.1]

centripetal acceleration The *acceleration* of a particle moving in a *circle*. The acceleration is directed towards the centre of the circle and has magnitude $\omega^2 r$, where ω is the *angular speed* of the particle about the centre of the circle, and r is the radius of the circle. [*DM*.3]

centripetal force The unbalanced *force* (whatever its origin) required to keep a body in *uniform circular motion* about a fixed point. When a *particle* of mass m moves around a circle of radius r with uniform *angular speed* ω (and therefore uniform *speed* $v = r\omega$), its *acceleration* is always directed towards the centre of the circle and has magnitude $a = r\omega^2 = v^2/r$. It follows from *Newton's second law of motion* that such a particle must be subject to an unbalanced force, directed towards the centre of the circle, with magnitude $F = mr\omega^2 = mv^2/r$; this is the centripetal force. [*PM*.1]

Chandler wobble A somewhat irregular movement of the Earth relative to its axis of rotation that contributes to the phenomenon of polar motion. The Chandler wobble has an approximate period of 430 days, and causes the North Pole to trace out a roughly circular path on the Earth's surface, with an approximate radius of 6 m. A major contribution to the Chandler wobble arises from the misalignment of the Earth's *angular momentum* with its axis of maximum *moment of inertia*, since this leads to a torque-free *angular acceleration*. (This effect is further modified by distortions of the Earth made possible by its lack of perfect rigidity.) [*PM*.4]

chaotic See *deterministic chaos*. [*PM*.5]

charge See *electric charge*. [*SFP*.1]

charge number The charge number of a particle is its charge divided by e (the magnitude of the charge of an electron). [*QPM*.4]

charge sharing The process by which an uncharged body can be charged by receiving some of the *charge* from a charged body with which it makes contact. (Compare with *induction* in electrostatics.). [*SFP*.1]

charge to mass ratio of the electron The ratio of the *charge*, $-e$, to the mass, m_e, of an electron. It is more easily measured than either the charge or the mass separately and has the value

$-e/m_e = -1.759 \times 10^{11}\,\mathrm{C\,kg^{-1}}$. [*SFP*.1]

Charles's law A law stating that; at constant *pressure*, the volume of a fixed mass of an *ideal gas* is proportional to its *absolute temperature*. [*CPM*.1]

charm A dimensionless quantity that is conserved in *strong* and *electromagnetic interactions*, but not in *weak interactions*. [*QPM*.4]

charm quark One of the six types of *quark*. It is the only quark to have non-zero *charm*. [*QPM*.4]

chromatic aberration The blurring caused by the separation of the colours in the image produced by a *lens*. Because the *refractive index* of a material varies with optical frequency, blue light is focused more strongly by a glass (or similar) lens than is red light. Hence, the *focal point* of the lens is not uniquely defined for general illumination, with the result that images of objects illuminated with white light will be subjected to a rainbow-like blurring. *Mirrors* do *not* suffer from chromatic aberration. [*DFW*.3]

ciliary muscle The muscle tissue within the eye which is used to change the shape of the eyelens (either squashing or stretching it), thereby changing its *focal length* and so enabling it to bring objects at different distances to a sharp focus on the *retina*. [*DFW*.3]

circle The geometrical figure formed from all points in a plane that are at a common distance from a given point. The given point is called the centre of the circle, and the common distance is called the radius of the circle. (See also *equation of a circle*.) [*DM*.3]

Clarke orbit A name sometimes used to describe the 24-hour equatorial orbit in which a satellite, orbiting in

the same sense that the Earth rotates, maintains a fixed position as seen from the Earth. This is the orbit used by geosynchronous communications satellites. [*DM*.3]

classical continuum approximation The approximation of treating the numerous, narrowly separated, quantized *translational energy levels* associated with a gas of particles in a macroscopic container, as a continuous distribution of possible energies. Treating the energy levels in this way justifies the introduction of a *density of states* function. The approximation is valid when the *de Broglie wavelength* of a typical particle in the gas is much less than the length that characterizes its container. [*QPM*.1]

classical physics One of the major subdivisions of physics that should be compared and contrasted with *quantum physics*. Classical physics is often taken to consist of those subjects, such as *mechanics*, *electromagnetism* and *thermodynamics*, that were already well-defined by the year 1900, along with their direct developments in the twentieth century. [*RU*.1]

Clausius's statement of the second law of thermodynamics The statement that; no *cyclic process* is possible which has, as its sole result, the transfer of *heat* from a cooler body to a hotter one. [*CPM*.3]

closed system A *system* that can exchange no *matter* with its *environment*. [*CPM*.3]

cloud chamber A device for detecting *elementary particles*, based on observing the trails of tiny droplets left by charged particles as they pass through a supersaturated vapour (i.e. a vapour that is temporarily above its condensation point). [*QPM*.4]

coefficient of dynamic viscosity The *constant of proportionality* η in the relation

$$\frac{F}{A} = \eta \times \left| \frac{\Delta v_x}{\Delta x} \right|$$

between the magnitude of the *viscous force* per unit area, F/A, acting on each of two adjacent layers of fluid, and the magnitude of the *velocity gradient* at the interface between those layers. (Note that $\Delta v_x/\Delta x$ provides an approximation to the exact velocity gradient dv_x/dx.)

The value of η depends on the relative difficulty with which a given fluid flows, and hence the resistance that an object encounters in moving through that fluid. According to *Stokes' law*, when a sphere of radius R moves through a fluid of viscosity η at constant speed v, the force which opposes that motion is of magnitude $F = 6\pi\eta Rv$. The coefficient of dynamic viscosity is sometimes simply referred to as the coefficient of viscosity, or just the viscosity of the fluid. The *SI* unit of coefficient of viscosity is $\mathrm{N\,s\,m^{-2}}$. [*PM*.1; *CPM*.4]

coefficient of mutual inductance The *constant of proportionality* M in the relation

$$|V_2(t)| = M \times \left| \frac{di_1(t)}{dt} \right|$$

between the magnitude of the mutually *induced EMF* in a secondary coil of wire and the magnitude of the rate of change of *current* in the primary coil of wire, where the two coils have a common *magnetic flux* linkage, as in a *transformer*. The value of M depends on the construction of the two coils. For two long cylindrical solenoids, with complete magnetic flux linkage between them, $M = \mu A N_1 N_2/l$, where μ is the permeability of the core of each solenoid, A is their cross-sectional area, l is their length, and N_1 and N_2 are the number of turns on the primary and secondary coils, respectively. The coefficient of mutual inductance is sometimes simply referred to as the *mutual inductance*. The *SI* unit of mutual inductance is the *henry*, represented by the symbol H, where $1\,\mathrm{H} = 1\,\mathrm{V\,s\,A^{-1}}$. (See also *coefficient of self-inductance*.) [*DFW*.1]

coefficient of self-inductance The *constant of proportionality* L in the relation

$$|V_{\text{ind}}(t)| = L \times \left| \frac{di(t)}{dt} \right|.$$

between the magnitude of the self-*induced EMF* in a coil and the magnitude of the rate of change of *current* in the coil. The value of L depends on the construction of a coil. For a long cylindrical solenoid, $L = \mu A N^2/l$, where μ is the permeability of the core of the solenoid, A is its cross-sectional area, l is its length and N is the number of turns. The coefficient of self-inductance is sometimes simply referred to as the *self-inductance*, or just the *inductance* of the coil. The *SI* unit of self-inductance is the *henry*, represented by the symbol H, where $1\,\mathrm{H} = 1\,\mathrm{V\,s\,A^{-1}}$. (See also *coefficient of mutual inductance*.) [*DFW*.1]

coefficient of sliding friction The constant of proportionality μ_{slide} in the relation

$$F = \mu_{\text{slide}} N$$

between the magnitude F of the frictional force on a body as it slides over a solid surface, and the magnitude N of the *normal reaction force* that the surface exerts on the body.

The value of μ_{slide} depends on the surfaces involved and their state of lubrication, but is largely independent of other factors, including the area of contact and the speed of the object. In any given situation, the coefficient of sliding friction is usually slightly smaller than the *coefficient of static friction*. [*PM*.1]

coefficient of static friction The constant μ_{static} in the relation

$$F = \mu_{\text{slide}} N$$

between the magnitude F of the maximum frictional force that can oppose the sliding motion of a body over a solid surface, and the magnitude N of the *normal reaction force* that the surface exerts on the body.

The value of μ_{static} depends on the surfaces involved and their state of lubrication, but is largely independent of other factors, including the area of contact. In any given situation, the coefficient of static friction is usually slightly higher than the *coefficient of sliding friction*. [*PM*.1]

coefficient of viscosity See *coefficient of dynamic viscosity*. [*PM*.1]

coherence length For an electron in a *superconductor*, the distance across which the wavefunction spreads with sufficient amplitude that it will interact with a second electron to bind and form a *Cooper pair*. The coherence

length is long in pure well-formed metallic crystals, but it is reduced by electron scattering and can be very short in alloys and polycrystalline compounds. The main significance of the coherence length is that when it is shorter than the *penetration depth* for a magnetic field, the bulk of the superconductor can be threaded by flux lines to give a *type II superconductor*. [*QPM*.2]

coherent A term used to describe the relationship between different processes that might allow an event to occur when the contributions of those different processes can be represented by a sum of terms in a *wavefunction* (as opposed to a sum of probabilities). Coherence is generally regarded as a necessary condition for interference. [*QPI*.4]

coherent source A spatially extended source of *waves* is said to be coherent if the emissions contributed by the various regions of the source are always in *phase* with one another. For example, if *plane waves* of light impinge *normally* on a pair of slits in a screen, the slits act as a secondary source of light (by the *Huygens principle*); this source is coherent because the two slits produce light waves that are in phase at the point of emission. [*DFW*.2]

collapse of the wavefunction The process whereby a *wavefunction* is supposed to undergo an abrupt and unpredictable change due to a measurement. The result of the collapse is conventionally supposed to be an *eigenstate* of the measured *observable*, corresponding to the *eigenvalue* that was the result of the measurement. Wavefunction collapse is not a feature of the time evolution described by the *time-dependent Schrödinger equation*. [*QPI*.4]

colliding beams A term used to describe particle physics experiments in which a beam of particles is directed at another beam of particles, moving in more or less the opposite direction. (Contrast with *fixed target*.) [*QPM*.4]

collision A brief interaction between two or more particles or bodies in close proximity. [*PM*.3]

colour A property of *quarks* that is an essential part of the gauge theory of the *strong interaction*. Consequently, the theory is called *quantum chromodynamics*, or QCD. [*QPM*.4]

comet A small body (typically 10 km or so in diameter) that orbits the Sun in a highly eccentric orbit. When it is sufficiently close to the Sun, dust and gas stream from the surface of the comet and form a characteristic tail that may be more than a million kilometres in length and visible from Earth. [*DM*.3]

commutative The property of a product of factors whereby the result is independent of the order in which the factors are multiplied together. An ordinary algebraic product of scalar quantities x and y is commutative since $xy = yx$ for all possible choices of x and y. The *scalar product* of two arbitrary vectors is similarly commutative since $\boldsymbol{a} \cdot \boldsymbol{b} = \boldsymbol{b} \cdot \boldsymbol{a}$. However, the vector product $\boldsymbol{a} \times \boldsymbol{b}$ is *not* commutative because $\boldsymbol{a} \times \boldsymbol{b} = -\boldsymbol{b} \times \boldsymbol{a}$. [*PM*.4]

complementarity See *principle of complementarity*. [*QPI*.4]

completely inelastic collision A *collision* in which the colliding bodies stick together, resulting in the maximum loss of *kinetic energy* consistent with *conservation of momentum*. [*PM*.3]

components A set of *scalar* quantities that can be used to specify a *vector*. See *Cartesian components*. [*DM*.2]

compound A pure substance formed by the chemical combination of different *elements*. [*CPM*.1]

compound microscope See *microscope*. [*DFW*.3]

compressibility The fractional decrease in volume of a substance per unit increase in the *pressure* acting on it, under specified conditions (e.g. at constant *temperature*). [*CPM*.1]

concave lens See *diverging lens*. [*DFW*.3]

concave mirror See *converging mirror*. [*DFW*.3]

conduction (of heat) A mechanism of *heat* transfer in which collisions between *atoms* or *molecules* cause energy to be transferred from regions where the average molecular speed is relatively high (corresponding to high *temperature*) to regions where the average molecular speed is somewhat lower (corresponding to low temperature). [*CPM*.3]

conduction band The lowest unfilled *energy band* in a solid, containing the *conduction electrons* for a *semiconductor*. This band is completely empty in an *insulator* or semiconductor at very low temperatures but becomes partly populated due to thermal excitation of electrons from the *valence band* as the temperature rises. [*QPM*.2]

conduction electrons See *free electrons*. [*QPM*.1]

conductor A material that allows *electric charge* to flow with relative ease. Conductors contain free electric charges that are able to move throughout the whole body of the material under the influence of applied *electric fields* or *potentials*. The free charges are often electrons (e.g. in metals), but can also be positive charges such as *ions* in a solution. (Contrast with *insulator*.) [*SFP*.1]

configuration A microscopically detailed description of the condition of a system, sufficiently detailed for the purposes of statistical mechanical analysis. In classical *statistical mechanics*, the configuration of a *gas* is defined by specifying which *molecules* are in which *phase cells*. The configuration of a system, such as a gas, is also known as its microstate. [*CPM*.2; *CPM*.3]

In quantum mechanics, identical particles are *indistinguishable*, and a configuration of a system of identical particles is defined by giving the numbers of particles in each *quantum state*. [*QPM*.1]

confinement The mechanism arising from the interaction of *quarks* and *gluons* that prevents them from being observed as free particles. It is generally supposed that this is a consequence of *quantum chromodynamics*, but despite a good deal of supporting evidence, this has still not been rigorously proved. [*QPM*.4]

conic sections Any of the curves produced by the intersection of a plane and a cone is called a conic section. The curves that belong to this family include the *circle*, the *ellipse*, the *parabola* and the hyperbola. Each such curve is described by the set of all points (x, y) that satisfy an equation of the form

$$ax^2 + 2hxy + by^2 + 2gx + 2fy + c = 0$$

for specific choices of the constants *a, b, c, f, g, h*. [*DM*.2]

conservation law Any law that expresses the constancy in time of a physical quantity (such as energy or momentum) under specified circumstances. Such laws are often referred to as *conservation principles*. [*RU*.1; *QPM*.4]

conservation of angular momentum The principle that, in any system, the total *angular momentum* about any point remains constant as long as no net external *torque* about that point acts on the system. [*PM*.4]

conservation of charge The principle that the total *electric charge* of any system remains constant, provided that no matter enters or leaves the system. Thus, if a certain amount of positive charge is created in a process, an equal amount of negative charge must also be created. [*SFP*.1]

conservation of energy The principle that the total *energy* of any *isolated system* is constant. A more informal statement of this principle is that energy may neither be created nor destroyed. [*RU*.1; *PM*.2]

conservation of linear momentum The principle that the total *linear momentum* of any isolated system is constant. [*PM*.3]

conservation of mass The principle, in classical *Newtonian mechanics*, that the *mass* of any system remains constant, provided no matter enters or leaves the system. A more informal statement of this principle is that mass cannot be created or destroyed. (The development of *special relativity* has shown that this principle is not generally true, though it is still of considerable value and is widely used within Newtonian mechanics.). [*RU*.1, *PM*.1]

conservation of mechanical energy The principle that in an *isolated system*, in which only *conservative forces* act, the total mechanical energy (i.e. the sum of the kinetic and potential energies) is constant. [*PM*.2]

conservation principle Any principle that expresses the constancy in time of a physical quantity (such as energy or momentum) under specified circumstances. Examples include the principles of *conservation of charge*, *conservation of energy*, *conservation of linear momentum* and *conservation of angular momentum*. [*PM*.1]

conservative force A *force* with the characteristic that the *work* it does when its point of application moves from one point to another, is independent of the route followed between those two points. (This is equivalent to the requirement that the work done by the force when its point of application moves around a closed loop is zero.) The gravitational force on a body of fixed mass is an example of such a force. [*PM*.2]

constant acceleration equations A set of equations relating the *displacement*, *velocity* and *acceleration* of a uniformly accelerating *particle*. For a particle accelerating along the *x-axis*, the equations are

$$s_x = u_x t + \tfrac{1}{2} a_x t^2$$

$$v_x = u_x + a_x t$$

$$v_x^2 = u_x^2 + 2a_x s_x$$

where s_x is the *displacement* of the particle at time t from its initial position at time $t = 0$; the initial velocity (at time $t = 0$) is u_x, and v_x is the final velocity at time t. The acceleration is a_x and must be constant for the equations to apply. [*DM*.1]

If the (constant) acceleration is specified by the vector $\boldsymbol{a}$ = constant, then

$$\boldsymbol{s} = \boldsymbol{u}t + \tfrac{1}{2}\boldsymbol{a}t^2$$

$$\boldsymbol{v} = \boldsymbol{u} + \boldsymbol{a}t$$

where $\boldsymbol{u}$ is the initial velocity, $\boldsymbol{v}$ is the velocity at time t, and $\boldsymbol{s}$ is the *displacement* from the *initial position* (not necessarily the origin) at time t. [*DM*.2]

constant of proportionality See *proportionality*.

constructive interference The phenomenon whereby two superposed *oscillations* or *waves* produce a resultant with a larger *amplitude* than either of the original oscillations or waves. The extreme case occurs when the oscillations or waves are exactly in phase, so that their phase difference is 0 or an integer multiple of 2π. [*DFW*.2]

contact force A force arising from the direct physical contact of one body with another. Such forces are ultimately electrical in nature since they actually arise from the electrical repulsion between atoms in the surfaces of the bodies. [*PM*.1]

convection A mechanism of *heat* transfer in which a hot body transfers energy to *fluid* with which it is in contact, causing the fluid to expand and decrease in *density* so that it rises through overlying denser fluid, thus carrying the transferred energy away from the source of the original heating. [*CPM*.3]

conventional current See *electric current*. [*SFP*.3]

converging lens A *lens* that is thicker at its centre than it is at its edges. Such a lens is also called a *convex lens*, or a *positive lens*, and has the property that it will increase the convergence (or reduce the divergence) of an incident *wavefront*. In the *real-is-positive convention*, a converging lens always has a positive *focal length*. [*DFW*.3]

converging mirror A mirror that increases the convergence (or reduces the divergence) of an incident *wavefront*. Such a mirror will have a concave shape but will behave like a converging (i.e. convex) lens; also called a *positive mirror*. In the *real-is-positive convention*, a converging mirror always has a positive *focal length*. [*DFW*.3]

convex lens See *converging lens*. [*DFW*.3]

convex mirror See *diverging mirror*. [*DFW*.3]

Cooper pair A pair formed from two electrons in quantum states with similar *wavefunctions*, but characterized by wave propagation in opposite directions, $\boldsymbol{k}$ and $-\boldsymbol{k}$, and opposite spin states. All the conduction electrons in a *superconductor* are bound in Cooper pairs at 0 K, but the pairing gradually disappears as the temperature rises towards the *superconducting transition temperature* T_C, due to thermal excitation across the *superconducting energy gap*. [*QPM*.2]

coordinate A value, determined within a *coordinate system*, that may be used to specify the *position* of a point. [*DM*.1; *DM*.2]

coordinate system An arrangement of *axes* (usually in three-dimensions) by means of which the position of any point (or *event*) can be specified. A *Cartesian coordinate system* has three mutually perpendicular axes, usually labelled x, y and z. [*DM*.1; *DM*.2; *DFW*.4]

coordinate transformation A set of equations that relates the coordinates of an event in one *frame of reference* to those of the same event in another frame of reference, which may be moving relative to the first. See, for example, *Galilean transformation* and *Lorentz transformation*, and see for comparison *velocity transformation*. [*DFW*.4]

Copenhagen interpretation An *interpretation* of *quantum mechanics* developed by Bohr, Heisenberg and others in the mid 1920s, and long regarded as the 'conventional' interpretation. It views the standard *formalism* as providing the most complete possible account of an individual system. Accepting the *indeterminacy* and *indeterminism* of quantum mechanics and Bohr's *principle of complementarity*, it presents probabilities as an inherent and unavoidable part of the theory, and treats *measurement* as an unanalysable interaction between a (logically) classical measuring apparatus and a *quantum system*. [*RU*.1; *QPI*.4]

coplanar The condition in which two or more geometrical objects (e.g. *lines* or *circles*) lie in the same plane. [*DM*.3]

Coriolis force A *fictitious force* that may be used to account for certain aspects of the motion of bodies observed from a rotating (non-inertial) *frame of reference*. The effect of the Coriolis force is to cause bodies moving towards or away from the axis of rotation to be deflected at right angles to their direction of motion. (This is exemplified by the rightward deflection of air masses travelling north or south in the Earth's Northern Hemisphere.) By introducing such fictitious forces the motion of the bodies may be made to conform with the predictions of Newton's laws, which do not, strictly speaking, apply in such frames. (See also *centrifugal force*.) [*PM*.1]

cornea The transparent front part of the eye casing. It is a component of the complete eyelens system; together with the *aqueous humour*, it contributes the major part of the eye's focusing power: the cornea + aqueous humour combination acts as a fixed *focal length converging lens* with a *power* of about 40 *dioptres*. [*DFW*.3]

correspondence principle A principle asserting that; in the classical limit (usually associated with large *quantum numbers* and therefore with macroscopic as opposed to microscopic systems), the predictions of *quantum mechanics* agree with those of *classical physics*. [*QPI*.2]

cosine function See *trigonometric functions*. [*DM*.3]

cosmic background radiation *Thermal radiation* at a temperature of about 3 K which bathes the whole Universe. It reaches its peak intensity in the microwave part of the spectrum and is sometimes referred to as cosmic microwave background radiation for that reason. It is thought to consist of the cooled remnant of the high temperature thermal radiation that was in thermal equilibrium with cosmic matter for the first 300 000 years or so of the Universe's existence. The cooling is a direct consequence of the expansion of the Universe. [*QPM*.1]

cosmic ray Energetic particles that reach the Earth from outer space. [*QPM*.4]

coulomb The *SI* unit of *electric charge*, represented by the symbol C, where 1 C = 1 A s. It follows that the coulomb is the charge transferred by a steady current of one *ampere* flowing for one second. [*SFP*.1]

Coulomb energy A contribution to the *binding energy* that arises in the context of the *semi-empirical model* of atomic nuclei, due to the electrostatic repulsion between all pairs of *protons*. This contribution has little effect for small nuclei where the *strong nuclear force* dominates, but the Coulomb repulsion is a long-range force and the associated energy becomes increasingly important in large nuclei. [*QPM*.3]

Coulomb's law (in free space) A law that describes the *electrostatic force* on a stationary charged particle, due to another stationary charged particle, located some distance away, in a vacuum. Coulomb's law can be represented mathematically by the equation

$$\boldsymbol{F}_{\text{el}} = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}\hat{\boldsymbol{r}},$$

where $\boldsymbol{F}_{\text{el}}$ is the force on one of the particles, q_1 and q_2 are the charges, r is the distance between them, ε_0 is the *permittivity of free space* and $\hat{\boldsymbol{r}}$ is a *unit vector* directed towards the particle on which the force is acting from the other (source) particle. Thus, $\hat{\boldsymbol{r}} = \boldsymbol{r}/r$, where $\boldsymbol{r}$ is the position vector of the particle on which the force is acting, when the origin is taken to be at the position of the source particle. In agreement with Newton's third law, the existence of this force implies that there is also a force $-\boldsymbol{F}_{\text{el}}$ acting on the source particle. This is consistent with the rule that: like charges repel and unlike charges attract. [*SFP*.1]

covalent bond A kind of *bonding* that arises between *atoms* and which can lead to the formation of individual *molecules* or solids. In a covalent bond, unpaired *electrons* in the separated atoms are shared to form a pair with opposite *spin* states. The pair is concentrated between the two atoms and is therefore able to attract each electrically, thus creating the bond. Covalent bonds are *directional* and may become *saturated*. [*QPM*.2]

covalent solid A solid containing neutral atoms joined by *covalent bonds*, with high *bond directionality*. Examples include diamond and silicon where the bonds are directed in a tetrahedral arrangement to give an open structure with four neighbours around each atom. [*QPM*.2]

critical angle The limiting *angle of incidence* beyond which *total internal reflection* occurs. It is given by: $\sin i_{\text{crit}} = n_2/n_1$ for a ray of light travelling from a medium of *refractive index* n_1 into a medium of refractive index n_2. [*DFW*.2]

critical current density The maximum *electric current* per unit area that can flow in a *superconductor* without that superconductor reverting to its normal conducting state. When current flows in a superconducting material, in the usual way, a magnetic field is created with a maximum magnitude at the surface of the material. The field magnitude is proportional to the magnitude of the current, so if the

current flow is sufficiently great, the *critical magnetic field strength* B_C is reached at the surface and the material reverts to the normal state. [*QPM*.2]

critical damping The condition in which a *damped harmonic oscillator* just fails to oscillate and comes to rest especially rapidly. For an oscillating body of mass m, subject to a linear restoring force $-kx$, and to a linear damping force $-bv_x$, the motion will be critically damped when $b = 2\sqrt{km}$. [*PM*.2]

critical magnetic field strength The maximum magnitude, B_C, of applied magnetic field for which the *Meissner effect* can occur in a *superconductor*. At larger applied fields the flux penetrates the material destroying the *superconductivity*. The value of B_C is strongly temperature dependent, increasing from zero at the *superconducting transition temperature* T_C to a maximum at 0 K. [*QPM*.2]

critical point The point on the *PVT surface* of a substance that corresponds to the highest *temperature equilibrium state* in which the *liquid* and *gas* phases coexist. At the critical point, the distinction between liquid and gas phases is meaningless. [*CPM*.1]

cross product See *vector product*. [*PM*.4]

cross-section A measure of the probability that a certain kind of scattering will occur at a specified energy. It is often denoted by the symbol σ and has the units of area. Cross-sections are usually expressed in terms of the non-SI unit known as the *barn*, represented by the symbol b where $1\,\mathrm{b} = 10^{-28}\,\mathrm{m}^2$. A cross-section can be restricted to *elastic scattering* or may include both elastic and inelastic contributions, in which case it is known as the *total cross-section*. [*QPM*.4]

crystalline lens That part of the human eyelens system which, being made up of over 20 000 layers of transparent cellular material, can have its shape changed (under the action of the *ciliary muscle*) and thereby change the eyelens's overall *focal length*. (See also *cornea* and *aqueous humour*.) [*DFW*.3]

crystalline solid A *solid* in which the equilibrium positions of the constituent *atoms* form a regularly repeating pattern that exhibits *long-range order*. Such solids may form spontaneously when a large number of atoms or molecules condenses to form a solid, since they represent the structure of maximum *binding energy*, and hence of greatest stability. [*CPM*.1; *QPM*.2]

cube The cube of a quantity is the result of multiplying the quantity by itself and then multiplying the result by the original quantity again:

$$x^3 = x \times x \times x. \quad [DM.1]$$

cubic function A *polynomial function* of the form $f(x) = Ax^3 + Bx^2 + Cx + D$. [*DM*.1]

current See *electric current*. [*SFP*.3]

cycle The set of successive values that a *periodic function* passes through as its *argument* is increased by one *period*. For example, in the case of the periodic function $A\sin(\omega t + \phi)$, a cycle would consist of the succession of values between A and $-A$ that the function passes through as $\omega t + \phi$ increases by 2π. [*DM*.3]

cyclic accelerator A *particle accelerator* in which charged particles follow closed or nearly closed paths so that they can be accelerated repeatedly by the same parts of the machine. [*QPM*.4]

cyclic process A *process* in which the *system* returns to its initial *state*. [*CPM*.3]

cyclotron A *cyclic accelerator* in which a vertical magnetic field is used to bend the path of particles that circulate within two horizontal 'dee'-shaped metal cavities. The dees are separated by a small gap and are maintained at opposite voltages so that a horizontal electric field exists between them. In order to ensure that the electric field always causes the particles to speed up rather than slow down, it is necessary to apply an alternating voltage to the dees. The cyclotron is not suitable for accelerating particles to *relativistic energies*. [*QPM*.4]

cyclotron frequency The frequency, f_C, of the circular or helical motion of a charged particle in a uniform *magnetic field*. It depends only on the magnitude of the particle's charge to mass ratio $|q|/m$ and the *magnetic field strength* B:

$$f_C = \frac{|q|B}{2\pi m}. \quad [SFP.4]$$

cyclotron motion The circular motion of a charged particle in the plane perpendicular to a *magnetic field*. [*SFP*.4]

cyclotron radius The radius of the circle described by a particle undergoing *cyclotron motion* in a uniform *magnetic field*. [*SFP*.4]

cylindrical lens A lens whose surfaces are parts of cylinders. Such a lens will have focusing properties in the direction perpendicular to the straight side(s) of the cylinder, but have no focusing effect in the direction parallel to the straight side(s). For comparison, see *spherical lens*. [*DFW*.3]

cylindrical solenoid A coil of wire wound uniformly in such a way that successive turns are of the same diameter and coaxial. A 'long' solenoid is one in which the length greatly exceeds the diameter. When a current flows through such a long coil, a uniform *magnetic field* is produced inside the coil, parallel to its long axis, and of magnitude $B = \mu_0|i|N/l$, where N/l is the number of turns per unit length. The direction of the current is determined by the *right-hand grip rule*. [*SFP*.4]

damped See *damped harmonic oscillator*.

damped harmonic oscillator An oscillator, typically a particle of mass m on a spring, that is subject to a *linear restoring force* $-kx$, and to a linear damping force $-bv_x$, where x is the instantaneous displacement of the particle from its equilibrium position, v_x is the instantaneous velocity of the particle, and both k and b are positive constants. In the case of *light damping*, when b/m is small, the damped harmonic oscillator's displacement from equilibrium at time t is given by

$$x(t) = (A_0\,\mathrm{e}^{-t/\tau})\sin(\omega t + \phi)$$

where A_0 and ϕ are arbitrary constants, $\tau = 2m/b$, and the angular frequency ω has a value close to the natural frequency, $\omega_0 = \sqrt{k/m}$, of the corresponding undamped harmonic oscillator. As a result of the damping, the energy of a damped harmonic oscillator decreases with time. [*PM*.2]

damping constant The constant of proportionality b that relates the strength of the damping force to the velocity of the oscillator in the case of a *damped harmonic oscillator*. (Note that some authors use the term damping constant to mean b/m.) [*PM*.2]

dark adapted The state of the eye, brought about by subjecting it to a lengthy period of extremely low light level, in which the *pupil* has dilated to its maximum diameter (typically about 8 mm). [*DFW*.3]

daughter nucleus See *parent nucleus*. [*QPM*.3]

de Broglie formula The equation $\lambda_{dB} = h/p$ for the *de Broglie wavelength* of a material particle in terms of *Planck's constant*, h, and the magnitude of its (*relativistic*) *momentum*, p. The result is also valid for *photons*, which are massless. [*QPI*.1]

de Broglie wave See *probability wave*. [*QPI*.2]

de Broglie wavelength The wavelength (given by the *de Broglie formula*) which de Broglie's theory of *wave–particle duality* assigns to a material particle of given momentum. [*QPI*.1]

decay A general process whereby an (unstable) particle can spontaneously change into two or more other particles. [*QPM*.4]

decay constant See *exponential decay law*. [*QPM*.3]

decay width A quantity that arises in the study of hadron resonances, and which is inversely proportional to the mean lifetime of those short-lived particles. Hadron resonances are observed as resonance peaks when certain scattering cross-sections are plotted against energy. The decay width of a given resonance is represented by the full width of the resonance peak at the level where its height is half of its maximum value. The decay width of a resonance has the units of energy. [*QPM*.4]

decoherence effect The rapid destruction of *coherence* between the different parts of the wavefunction of a macroscopic system as a result of the interaction between that system and its environment. This is widely supposed to be responsible for the absence of macroscopic superpositions of the sort made famous by *Schrödinger's cat*. [*QPI*.4]

deep inelastic scattering A process in which very high-energy *electrons* collide with *protons* and behave (by undergoing relatively large deflections) as though they are striking point-like targets. The implication is that the point-like objects being struck are *quarks* within the proton. [*QPM*.4]

defects Imperfections in the regular arrangement of atoms in real crystals due to a variety of effects including; vacancies (missing atoms), *dislocations*, chemical impurities and polycrystal boundaries. [*QPM*.2]

defect scattering In *Pauli's quantum free-electron model* in metals, electrical *resistivity* is caused by the scattering of electron waves by *defects* in the crystal lattice and by *thermal scattering*. The defect scattering makes a contribution to the resistance that is roughly independent of temperature and proportional to the defect density. [*QPM*.2]

definite integral A mathematical expression indicating the limit of a sum, usually as some particular quantity becomes vanishingly small. Definite integrals can be thought of as representing the (signed) area under a given curve between given limits, and may be evaluated using a technique called *integration*. [*PM*.2]

deformed nuclei In their state of lowest energy, most nuclei tend to be spherically symmetric partly because of their *surface energy* which, for a given *mass number*, is a minimum for a sphere. For some heavy nuclei however, weak shell-effects overcome the effects of the surface energy and favour a rugby-ball shape. Such non-spherical nuclei are said to be deformed. [*QPM*.3]

degeneracy The phenomenon whereby more than one *quantum state* is associated with a particular *energy level* in a given system. Any energy level that corresponds to more than one quantum state is said to be degenerate. [*QPI*.2]

degrees of freedom Each independent term, involving the square of a displacement, velocity, angular displacement or angular velocity, that appears in the expression for the total energy of a particle is said to correspond to a degree of freedom. The number of degrees of freedom, f, is the number of such squared terms. [*CPM*.2]

density The ratio of mass to volume for a homogeneous *system*. It is possible to define the density at a given point in any system by taking a small volume element around that point and evaluating the ratio of mass to volume for that volume element. [*CPM*.1]

density of states function A function $D(E)$ that describes, in the *classical continuum approximation*, the way in which the states of a quantum gas are distributed with respect to energy. The function is such that the number of quantum states with energies in the range between E and $E + \Delta E$ is $D(E)\,\Delta E$. For a gas of distinguishable molecules, $D(E) = B\sqrt{E}$, for a gas of photons $D_p(E) = CE^2$ and for a gas of electrons $D_e(E) = 2B\sqrt{E}$, where B and C are constants. (See also *density of states function for electrons* and *density of states function for photons*.) [*QPM*.1]

density of states function for electrons The distribution with respect to energy of the states available to an electron in *Pauli's quantum free-electron model* of a metal of volume V, is described, in the *classical continuum approximation* by the *density of states function*

$$D_e(E) = B'\sqrt{E}$$

where $B' = \dfrac{4\pi V}{h^3}(2m)^{3/2} = (1.06\times10^{56}\ \mathrm{J}^{-3/2}\ \mathrm{m}^{-3})V$.

(There is a factor of 2 in B' to account for the two electron *spin* states corresponding to each *translational quantum state*.) [*QPM*.1]

density of states function for photons The distribution with respect to energy of the quantum states available to *photons* inside a cavity of volume V is described, in the *classical continuum approximation*, by the *density of states function*

$$D_p(E) = CE^2$$

where $C = 8\pi V/h^3c^3 = (3.206 \times 10^{75}\ \mathrm{J}^{-3}\ \mathrm{m}^{-3})V$. [*QPM*.1]

dependent variable A quantity whose value is determined by the value of one or more other variables, usually referred to as *independent variables*. [*DM*.1]

depletion region (or depletion layer) The layer of material extending along the boundary in a *p–n junction*. In this depletion region the *electrons* and *holes* have recombined to leave bare *donor* and *acceptor* ions that create an electric field directed across the junction from the n-side to the p-side. [*QPM*.2]

depth of field The range of distances within the object field over which an acceptably in-focus image is produced at a fixed image (or film) plane. [*DFW*.3]

depth of focus The range over which the lens-to-image distance can be adjusted without the image of a fixed object becoming unacceptably blurred. [*DFW*.3]

derivative The derivative of a *function* $f(y)$ with respect to y is another function of y, sometimes called the *derived function*, that is equal to the rate of change of $f(y)$ with respect to y at each value of y. Its value at any given value of y is equal to the ratio $\Delta f/\Delta y$ in the limit as Δy becomes very small and is usually written as $\frac{df}{dy}$. The value of $\frac{df}{dy}$ at any given value of y is also equal to the *gradient* of the *graph* of f plotted against y at the given value of y. [*DM*.1]

derived function See *derivative*. [*DM*.1]

destructive interference The phenomenon whereby two superposed *oscillations* or *waves* produce a resultant with a smaller amplitude than either of the original oscillations or waves. The extreme case occurs when the oscillations or waves are exactly out of *phase*, so that their *phase difference* is an odd integer multiple of π. [*DFW*.2]

determinism The notion that the past completely determines the present, and hence the future. [*RU*.1]

deterministic A term used to indicate the possibility, in principle, of making exact and complete predictions about the future, given sufficiently exact and complete information about the past. Newtonian mechanics is an example of a deterministic theory, but *quantum mechanics* is not deterministic. (See also *deterministic chaos* and *deterministic system*.) [*QPI*.2]

deterministic chaos A type of behaviour characterized by: (i) Deterministic rules that describe how the state of a system at a particular time determines the state of the system at a later time. (For simple systems the rules may be written down, but many real systems are too complex to allow this.) (ii) Unpredictable outcomes, because a small uncertainty in the initial state of a system causes differences in subsequent behaviour that increase exponentially with time, so after a sufficiently long time the state will be effectively unpredictable. [*PM*.5]

deterministic system A system for which there are well-defined rules, or equations, governing changes at all times. If these rules are known, they can be used to determine the state of the system at a later time from information about the state of the system at an earlier time. [*PM*.5]

developer (photographic) A chemical that is used to convert the exposed transparent crystals of *silver halide* in photographic *film* into opaque black grains of metallic silver, while leaving the unexposed crystals intact. When the film is then treated with *fixer* and washed, a *negative* image of the photographed object is produced. [*DFW*.3]

diamagnetic A term used to describe materials which, when placed in a *magnetic field*, become magnetized in the direction opposite to the applied field. The total magnetic field within the material is therefore less than the applied magnetic field that causes the *magnetization*. (Contrast with *paramagnetic*.) [*SFP*.4]

diatomic A term used to describe a *molecule* consisting of two *atoms* bound together by interatomic forces. [*CPM*.1]

dielectric See *insulator*. [*SFP*.2]

differential equation An equation involving derivatives, such as the *simple harmonic motion equation*

$$\frac{d^2x(t)}{dt^2} = -\omega^2 x(t)\,.$$

The solution of a differential equation is generally a function, and involves a number of *arbitrary constants* in addition to the parameters (such as ω) that appear in the equation itself. In the case of the s.h.m. equation, for example, the *general solution* is $x(t) = A\sin(\omega t + \phi)$, where A and ϕ are arbitrary constants. [*DM*.3; *PM*.1]

differentiation A mathematical process that allows the *derivative* of a function to be determined. [*DM*.1]

diffraction The phenomenon whereby waves are able to bend round obstacles or spread from apertures. According to the *Huygens principle*, each point on a *wavefront* can be regarded as a small source of secondary *waves*. When a wavefront meets a partial obstacle, secondary waves spread out from the unimpeded parts of the wavefront and it is this that gives waves their ability to 'bend round corners'. [*DFW*.2]

diffraction equation The equation

$$n\lambda = d\sin\theta_n$$

that relates the *wavelength* λ of *plane waves* normally incident on a *diffraction grating* of *grating spacing* d, to the angle θ_n between the direction of the incident beam and the direction of the diffracted beam of *order of diffraction* n. [*DFW*.2]

diffraction grating A series of uniformly spaced narrow slits of equal width, which act as a *coherent source* of *waves* and give rise to *interference fringes* when illuminated with a *plane wave*. The positions of successive *orders of diffraction* in the *diffraction pattern* are given by the *diffraction equation*. [*DFW*.2]

diffraction pattern The pattern of *interference fringes* produced by the *superposition* of *waves* that have been *diffracted* by an object such as a *diffraction grating*. Maxima and minima of intensity in the pattern are caused by *constructive interference* and *destructive interference*, respectively. [*DFW*.2]

dimension of a coordinate system The minimum number of *coordinates* needed to specify uniquely the position of every *point* in the region covered by a *coordinate system*. [*DM*.1]

dioptre A unit used to express the *power* of a *lens* and defined as $1\ \mathrm{D} = 1\ \mathrm{m}^{-1}$. [*DFW*.3]

direct current An electric current that maintains a constant direction (although it may vary in magnitude). Contrast with *alternating current*. [*DFW*.1]

direct current generator A device in which an externally supplied *torque* causes a coil of wire to rotate in a *magnetic field*, thus *inducing* an electric current in the coil that can be used to produce a *direct current* in an external circuit. The direct current is drawn off by means of a single split metal ring attached to either end of the coil and connected via brushes to the external circuit. The way in which the current is drawn off distinguishes this device from an *alternating current generator*. [*DFW*.1]

direct current motor A device in which an externally supplied *direct current* causes a coil of wire to rotate in a magnetic field. For example, if a direct current is fed into a *direct current generator*, then the Lorentz force acting on the conduction electrons in the coil (which sits in a magnetic field) will cause the coil to rotate about its axis. [*DFW*.1]

direction The property of a *vector* that determines its orientation. A common way of expressing the direction of a vector is to specify the angle between a particular *axis* or reference line and the vector. For example, in two dimensions, it is customary to specify the direction of a vector in terms of the angle (measured anticlockwise) between the positive x-axis and the vector. An alternative method is to specify the *components* of the vector relative to a particular coordinate system. [*DM*.2]

direction of propagation The direction in which a *travelling wave* transports *energy*. [*DFW*.2]

dislocation A type of *defect* in a crystal where, for example, an incomplete sheet of atoms terminates along a line. The movement of dislocations accounts for metals being *ductile*. [*QPM*.2]

dispersion The phenomenon whereby different colours of *light* (or different frequencies of *electromagnetic radiation*) are spread out when they cross an interface between two media of different refractive index. It occurs because the *refractive index*, and hence the *angle of refraction*, varies slightly with *frequency*. [*DFW*.2]

displacement (vector) The quantity that describes the difference between the position of a point and the position of a specified reference point. In the case of a particle moving in one dimension, along the x-axis, if the particle starts at position x_1 and moves to position x_2, then the displacement of the particle from its initial position is

$$s_x = x_2 - x_1.$$

The *magnitude* of this displacement is the *distance* s between the two points, so $s = |s_x|$.

Displacement is a vector quantity characterized by a direction as well as a magnitude. In one dimension the sign of s_x suffices to indicate the direction, but in two or three dimensions some other method must be used to indicate direction. This is often achieved by expressing the displacement vector in terms of its (Cartesian) components. Thus, if point P_1 has the position vector $\boldsymbol{r}_1 = (x_1, y_1, z_1)$ and point P_2 has the position vector $\boldsymbol{r}_2 = (x_2, y_2, z_2)$, then the displacement $\boldsymbol{s} = (s_x, s_y, s_z)$ from P_1 to P_2 is defined by

$$\boldsymbol{s} = \boldsymbol{r}_2 - \boldsymbol{r}_1 = (x_2 - x_1, y_2 - y_1, z_2 - z_1).$$

In this case the distance between the two points is given by

$$s = |\boldsymbol{s}| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}\ .$$

Note that a displacement is entirely specified by its magnitude and direction; it is not tied to any particular starting point or finishing point, even though such points may be used to specify it. [*DM*.1; *DM*.2]

displacement–time graph A graph showing how the *displacement* of a *particle* from a given reference point depends on time. It is conventional to plot the displacement on the vertical *axis* and the time on the horizontal axis. The gradient of the *displacement–time graph* at any particular time is equal to the *velocity* of the particle relative to the reference point at that time. [*DM*.1]

distance The quantity that describes the *magnitude* of the *displacement* of one point from another. For example, in one dimension, the distance between two points with position x_1 and x_2 is

$$s = |s_x| = |x_2 - x_1|. \quad [DM.1]$$

distance of closest approach The smallest distance between an incident particle and its target. It is exemplified by the smallest distance between an *α-particle* and the centre of a target *nucleus* in a head-on collision, i.e. one with an *impact parameter* of zero. [*QPI*.1]

distribution function A function which, when multiplied by a small range of a given variable, tells us the fraction of particles for which the given variable has values in the given range. *Gases* are commonly described in terms of their *speed distribution function* or *translational energy distribution function*. (See *Maxwell–Boltzmann energy distribution* for an example.) [*CPM*.2]

diverging lens A *lens* that is thinner at its centre than at its edges. It has the property that it will increase the divergence (or reduce the convergence) of an incident *wavefront*. Also called a *concave lens*, or a *negative lens*. In the *real-is-positive convention*, a diverging lens always has a negative *focal length*. [*DFW*.3]

diverging mirror A mirror that increases the divergence (or reduces the convergence) of an incident *wavefront*. Such a mirror will have a convex shape but will behave like a diverging (i.e. concave) lens. Also called a *negative mirror*. In the *real-is-positive convention*, a diverging mirror always has a negative *focal length*. [*DFW*.3]

domain A region in a *ferromagnetic* material in which the alignment of atomic *magnetic dipoles* is practically perfect. In an unmagnetized sample of iron, a typical domain is a few micrometres (10^{-6} m) across. When the iron is magnetized, domains in which the atomic magnetic dipoles are aligned parallel to the applied *magnetic field* grow, while others shrink. [*SFP*.4]

domain wall The boundary between two neighbouring *domains* in a ferromagnetic material and is typically only a few atoms in thickness. [*SFP*.4]

donors Impurity atoms added to a *semiconductor* to produce an *n-type* material. They have more *valence*

electrons than are required for bonding and therefore release one or more electrons into the *conduction band* of the semiconductor, thus creating free electrons there. In silicon, the donor atoms are often arsenic or phosphorus. [*QPM*.2]

doping The practice of adding a small carefully controlled amount of impurity to an *intrinsic semiconductor* material in order to make it an *extrinsic semiconductor*. [*QPM*.2]

Doppler effect The effect that causes the observed frequency of the *waves* from a source to depend on the relative motion of the source and the observer. If the relative motion is such that the source and the observer approach each other, the observed *frequency* is higher than the emitted frequency (the observed *wavelength* is shorter). If the relative motion is such that the source and observer recede from each other, the observed frequency is lower than the emitted frequency (the observed wavelength is longer). The Doppler effect is widely used to measure the speed of approach or recession of a source of radiation, particularly in astronomy. [*DFW*.2]

dot product See *scalar product*. [*PM*.2]

double-slit diffraction pattern The characteristic pattern of illumination (featuring well-defined maxima and minima of intensity) observed on a screen that is far from an illuminated pair of narrow parallel slits. The slits act as a secondary *coherent source* of *waves*. The maxima in the pattern occur at angles θ_n to the incident beam, where θ_n satisfies the *diffraction equation*. [*DFW*.2]

down quark One of the six types of *quark*. [*QPM*.4]

drag A force that acts on a body moving through a *fluid*. Drag acts in a direction that is opposite to the body's direction of motion. [*CPM*.4]

drift speed The drift speed of a collection of particles is the magnitude of the average velocity of those particles. For example, when an electric field $\mathscr{E}_x$ is applied to a metal wire, the conduction *electrons* undergo periods of acceleration in the direction opposite to $\mathscr{E}_x$ between collisions. This results in a drift of the electron gas at a constant average speed characterized by the drift speed

$$v_{\rm d} = (e\mathscr{E}_x/m)(\lambda/\langle v \rangle)$$

where λ is the *mean free path* and $\langle v \rangle$ is the average thermal electron speed. [*SFP*.3; *QPM*.2]

drip lines The boundary lines in the *Z–N plane* (a plot of *atomic number* against *neutron number*), between which all nuclei are expected to be found. [*QPM*.3]

driven damped harmonic oscillator An oscillator, typically a particle of mass m on a spring, that is subject to a *linear restoring force* $-kx$, a linear damping force $-bv_x$, and an externally imposed periodic driving force, usually of the form $F_x^{\rm drive} = F_0\cos(\Omega t)$. The instantaneous displacement $x(t)$ of such an oscillator can be written as the sum of two terms $x_{\rm dec} + x_{\rm dri}$ where $x_{\rm dec}$ represents a decaying transient motion, similar to that of a *damped harmonic oscillator*, and $x_{\rm dri}$ represents a steady motion, due to the driving force, that will persist after the decaying motion has died away. After a sufficiently long time, only the steady motion will remain and it may be described by

$$x(t) = A\sin(\Omega t + \phi)$$

where Ω is the driving (angular) frequency of the applied force and A and ϕ are (non-arbitrary) constants. The value of the steady-state amplitude A is given by

$$A = \frac{F_0/m}{\sqrt{(\omega_0^2 - \Omega^2)^2 + (\Omega b/m)^2}}$$

where $\omega_0 = \sqrt{k/m}$. This implies that the oscillator will enter a state of *resonance*, characterized by relatively large values of A, when ω_0 is close to Ω. The energy of a driven damped oscillator that has entered its steady state is constant, the driving force supplies energy to the oscillator at the same rate that it is dissipated by the damping force. This rate is a maximum when the oscillator is driven at its natural frequency. [*PM*.2]

driving frequency The angular frequency, Ω, of the periodic force used to supply energy to a *driven damped harmonic oscillator*. [*PM*.2]

Drude's free-electron model A model in which the *free electrons* in a metal are treated as a classical gas with a *Maxwell–Boltzmann energy distribution*. The electrons are assumed not to interact with one another but to occasionally collide with the lattice ions. [*QPM*.1]

ductile The property, particularly associated with metals, that allows a solid material to be hammered or bent into a new shape and to flow to a limited extent if the applied stress is sufficiently great. [*QPM*.2]

Dulong–Petit law An empirical law stating that; all solid *elements* have *molar heat capacities* of about $3R$ ($= 25\,{\rm J\,K^{-1}\,mol^{-1}}$) where R is the *universal gas constant*. This law is valid for most elements at room temperature, but is not true for diamond at room temperature, nor for other substances at *temperatures* well below room temperature. The law applies to elemental solids well above their *Einstein temperatures*. [*CPM*.2; *CPM*.3; *QPI*.1]

dynamically similar A term used to describe the relationship between two *fluid* flows that are geometrically similar, and which have the same *Reynolds number*. [*CPM*.4]

dynamics The study of the relation between *forces* and changes in motion. [*PM*.1]

earthed The condition of a body connected to Earth by means of a *conductor*. The *electric potential* of such a body is equal to that of the Earth. [*SFP*.2]

eccentricity A measure of how much an *ellipse* departs from a circle. The eccentricity e of an ellipse with *semimajor axis* a and *semiminor axis* b is given by

$$e = \frac{1}{a}\sqrt{a^2 - b^2}\,. \quad [DM.3]$$

echo location A method of determining the position of an object relative to a source of sound. The method is based on distance measurements derived from the time taken for a *sound wave* to travel from its source to an object and then return to its source after being reflected by the object. [*DFW*.2]

eddy currents The *induced currents* set up in a solid piece of metal, such as the iron core of a solenoid or *transformer*. Eddy currents generally dissipate energy, and are deemed to be wasteful. However, they are utilized to good effect in devices such as the *induction furnace*, where the energy dissipated is used to melt a sample of metal. [*DFW*.1]

effective focal length In a *telephoto lens* system, two lenses separated by a certain distance behave optically in the same way as a single lens with a much longer *focal length*. Similarly, in a *Cassegrainian telescope*, the converging *primary mirror* and the diverging *secondary mirror* behave optically in the same way as a single converging mirror with a much longer focal length. This longer focal length in each case is achieved within a smaller physical length of the device, and is said to be the 'effective (or equivalent) focal length of the system'. [*DFW*.3]

efficiency (of a heat engine) The ratio of the net amount of *work* done by an engine to the net amount of *heat* transferred to the engine. [*CPM*.3]

eigenstate In the context of *quantum mechanics*, an eigenstate of a given *observable* is a state that allows only one possible outcome for a *measurement* of that observable. That predicted outcome is said to be the *eigenvalue* that corresponds to the eigenstate. (Note: this is not the most general definition of eigenstate. The term also arises in mathematical contexts without any reference to quantum mechanics or measurements.) [*QPI*.4]

eigenvalue See *eigenstate*. [*QPI*.4]

Einstein–Podolsky–Rosen argument An argument (in the modified form due to Bohm) concerning observations at two separate locations of the *spin* components of a pair of particles in an *entangled* state. The EPR argument shows that, *quantum mechanics* as conventionally formulated, includes non-local features and uses this to argue that quantum mechanics is incomplete. (See also *Bell's theorem*.) [*QPI*.4]

Einstein's photoelectric equation An equation that sets the maximum kinetic energy of an electron liberated in the photoelectric effect equal to the quantum energy of the incident radiation minus the work function of the target material:

$$\tfrac{1}{2}mv_{\max}^2 = hf - \phi. \quad [QPI.1]$$

Einstein's postulates (of special relativity) The foundations on which the *special theory of relativity* are built. The postulates are:

1 The principle of relativity: the laws of physics can be written in the same form in all inertial frames of reference.

2 The principle of the constancy of the speed of light: the speed of light (in a vacuum) has the same constant value in all *inertial frames of reference*.

[*DFW*.4]

Einstein's theory of heat capacities A theory predicting the *heat capacities* of solids, based on the assumption that each atom in the solid behaves as a three-dimensional quantized oscillator. The theory predicts that the molar heat capacity of any elemental solid at *absolute temperature T* is given by

$$C_{\mathrm{m}}(T) = 3Rx^2\mathrm{e}^x/(\mathrm{e}^x - 1)^2$$

where R is the *universal gas constant* and x represents the ratio of the solid's *Einstein temperature* to its absolute temperature. Though rather crude, the theory accounts for some of the observed departures from the classical *Dulong–Petit law* of heat capacities, according to which $C_{\mathrm{m}} = 3R$. [*QPI*.1]

Einstein temperature A parameter, θ_{E}, arising in *Einstein's theory of heat capacities*, that determines, at any given absolute temperature T, the extent to which the *molar heat capacity* of a specified elemental solid departs from the value $3R$ predicted by the classical *Dulong–Petit law*. The Einstein temperature of a given crystalline solid is given by $\theta_{\mathrm{E}} = hf_{\mathrm{v}}/k$, where h is Planck's constant, f_{v} is the frequency of vibration of the atoms in the solid, and k is *Boltzmann's constant*. [*QPI*.1]

elastic A term used to describe the ability of a body to recover fully from a distortion, as long as it is not stretched too far. [*PM*.1]

elastic collision A collision in which *kinetic energy* is conserved. [*PM*.3]

elastic scattering A scattering process in which the beam and target particles do not change their nature. [*QPM*.4]

electrical conductivity A measure of a material's ability to conduct electricity, defined as the reciprocal of the material's *resistivity* ρ; so $\sigma = 1/\rho$. The electrical conductivity of a material is numerically equal to the electric current that would flow in a slab of the material of length 1 m and cross-sectional area 1 m^2 when a potential difference of 1 V is maintained across its ends. The units of σ are $\Omega^{-1}\,\mathrm{m}^{-1}$. [*QPM*.2]

electrical energy The *potential energy* associated with a given distribution of *electric charges*. This energy is often regarded as being 'stored' in the *electric field* created by the charges. In the case of a charged *capacitor*, the electrical energy is $E_{\mathrm{el}} = \frac{1}{2}CV^2$, where V is the *potential difference* across the capacitor, and C is its *capacitance*. (Contrast with the *magnetic energy* of an inductor.) [*SFP*.2]

electric charge A fundamental property of matter that determines the electric and magnetic interactions of particles. It obeys the principle of *conservation of charge*. There are two types of charge, positive and negative. Protons in atomic nuclei are positively charged (with charge e) and electrons are negatively charged (with charge $-e$). According to *Coulomb's law*, charges experience *electrostatic forces*; like charges repel and opposite charges attract. According to the *Lorentz force law*, charges moving across a *magnetic field* experience *magnetic forces* in a direction perpendicular both to their direction of motion and to the magnetic field. The *SI* unit of electric charge is the *coulomb* (C). [*SFP*.1]

electric current The rate at which *electric charge* flows in a given direction across a fixed plane (Often the current flows in a wire and the plane is perpendicular to the wire.) If the total charge q in some region is changing with time due to the flow of an electric current into that region, then the instantaneous value of the electric current is given by $i = \mathrm{d}q/\mathrm{d}t$. In metal wires, the flow of electric current is actually caused by negatively

charged electrons moving in the opposite direction to that of the current. For this reason, the current is sometimes called the conventional current. The *SI* unit of electric current is the *ampere* (A). [*SFP*.3]

electric dipole Any system that produces an *electric field* similar to that of two electric charges of the same magnitude q, but with opposite signs, separated from one another by a fixed distance d. Such a system is characterized by an electric dipole moment of magnitude qd. [*QPM*.2]

electric field The vector quantity $\mathscr{E}(\boldsymbol{r})$ that determines the *electrostatic force* that would act on any charged particle placed at the point specified by the *position vector* $\boldsymbol{r}$. It is defined as the electrostatic force per unit test charge, so if $\boldsymbol{F}_{\text{el}}$ is the electrostatic force on a particle of *charge* q at point $\boldsymbol{r}$, then $\mathscr{E}(\boldsymbol{r}) = \boldsymbol{F}_{\text{el}}/q$. The electric field has both magnitude and direction at each point in space, so it is an example of a *vector field*, and electric fields due to different sources add vectorially at every point. For an important example of an electric field see *electric field due to a point charge*. At any point, the electric field component in a given direction is equal to minus the gradient of the *electric potential*, V, in that direction. For example, the x-component and the radial component are given respectively by $\mathscr{E}_x = -\mathrm{d}V/\mathrm{d}x$ and $\mathscr{E}_r = -\mathrm{d}V/\mathrm{d}r$. The *SI* unit of electric field is $\mathrm{N\,C^{-1}}$ or (equivalently) $\mathrm{V\,m^{-1}}$. [*SFP*.1, *SFP*.2]

electric field due to a point charge The *electric field* due to a *point charge* is spherically symmetric around the charge. If a charge Q is placed at the *origin*, the *electric field* at a point specified by the position vector $\boldsymbol{r}$ is

$$\mathscr{E}(\boldsymbol{r}) = \frac{Q}{4\pi\varepsilon_0 r^2}\hat{\boldsymbol{r}}$$

where $\hat{\boldsymbol{r}}$ is a *unit vector* in the direction of $\boldsymbol{r}$ and ε_0 is the *permittivity of free space*. Thus, the magnitude of the electric field depends only on the distance r from the charge and it is directed away from a positive charge or towards a negative charge. [*SFP*.1]

electric flux See *magnetic flux*.

electric generator See *alternating current generator* and *direct current generator*. [*DFW*.1]

electric motor See *alternating current motor* and *direct current motor*. [*DFW*.1]

electric potential The electric potential $V(\boldsymbol{r})$ at a point specified by the vector $\boldsymbol{r}$ is the *electrostatic potential energy* per unit *charge* at that point. So, if E_{el} is the electrostatic potential energy of charge q at a point $\boldsymbol{r}$, the electric potential at that point is

$$V(\boldsymbol{r}) = \frac{1}{q}E_{\text{el}}.$$

Electric potential has a scalar value at every point in space, so it is an example of a *scalar field*. The *SI* unit of electric potential is the *volt*, represented by the symbol V, where $1\,\mathrm{V} = 1\,\mathrm{J\,C^{-1}}$. [*SFP*.2]

electrode A conducting plate at which charged particles (usually *electrons*) are collected or emitted in a *cell*, *battery*, vacuum electronic device, etc. A positive electrode is called an *anode*, a negative electrode is called a *cathode*.

electrolyte A liquid that conducts electricity by virtue of the presence of *ions* in solution. [*SFP*.3]

electromagnetic induction The phenomenon, described by *Faraday's law* and *Lenz's law*, by which a changing *magnetic flux* through a circuit gives rise to an *induced EMF* around the circuit, and hence an *induced current* in the circuit. [*DFW*.1]

electromagnetic interaction The fundamental interaction between particles that possess electric charge. (See also *strong*, *weak* and *gravitational interaction*.) [*QPM*.4]

electromagnetic radiation Radiation comprising any part of the *electromagnetic spectrum*. [*DFW*.2]

electromagnetic spectrum The complete range of electromagnetic radiation, ranging from *gamma rays* at short *wavelengths* (high *frequencies*) through *X-rays*, *ultraviolet radiation*, *visible light*, *infrared radiation* and *microwaves* to *radio waves* at long wavelengths (low frequencies). [*DFW*.2]

electromagnetic wave A fluctuating pattern of *electric* and *magnetic fields*, in which each field takes the form of a *wave*. At any point in an electromagnetic wave, the electric and magnetic fields are mutually perpendicular, and each field is also perpendicular to the direction of propagation of the wave. The existence of such waves is implied by *Maxwell's equations*, which also predict that the waves will travel through a vacuum at the *speed of light*. Electromagnetic waves of appropriate *wavelength* (or *frequency*) may be used to model each of the kinds of *electromagnetic radiation* that comprise the *electromagnetic spectrum*. [*DFW*.2]

electromagnetism The branch of physics that encompasses all electrical and magnetic phenomena, including the interactions of *charges* and magnets with *electric* and *magnetic fields*, and the production and propagation of *electromagnetic waves*. [*RU*.1; *SFP*.4]

electromotive force (EMF) A quantity measured in *volts* that describes the ability of a device to drive a current around a circuit. The electromotive force of a device is equal to the *potential difference* between the terminals of the device when it is part of an open circuit (i.e. when no current is flowing). Sources of EMF include cells, batteries, thermocouples, photovoltaic cells and various devices based on *electromagnetic induction*, such as generators and transformers. In such devices the EMF may be alternatively defined as the ratio of the power supplied by the device to the current that it produces in a circuit. Note that electromotive force is not a force in the sense defined by Newton's second law. [*SFP*.3]

electron A kind of *elementary particle* with charge $-1.602 \times 10^{-19}\,\mathrm{C}$, mass $9.109\,56 \times 10^{-31}\,\mathrm{kg}$, and spin 1/2. The electron is a stable *lepton*. As far as is known, it has no internal structure, and is therefore regarded as a truly fundamental particle. Electrons are constituents of all *atoms*, and are responsible for many familiar properties of matter including *bonding*, chemical reactions and electrical conduction. [*CPM*.1; *QPM*.4]

electron capture A form of *β-decay* in which a nucleus absorbs one of its orbiting electrons, causing a proton to become a neutron and a neutrino to be emitted. [*QPM*.3]

electron charge The charge carried by the electron is $-e = -1.602 \times 10^{-19}$ C. [*SFP*.1]

electronegativity The property of an atom that measures its affinity for *electrons*. A strongly electronegative atom in a *covalent bond* with a less electronegative atom will take more than an equal share of the bonding *electron pairs*. This gives it a net negative electric charge leaving its partner with a net positive charge. In extreme cases, a complete transfer of one or more electrons to the more electronegative atom takes place and an *ionic bond* is formed by the electrostatic attraction between positive and negative ions. [*QPM*.2]

electron gun A source of electrons (usually of a specific energy). It is an arrangement of *anode* and *cathode* maintained at a large potential difference and in a highly evacuated region. Electrons are emitted from the cathode and attracted towards the anode, which is perforated so that the electrons may pass through as a fine beam. [*SFP*.2]

electronic configuration See *electronic structure*.

electronic structure The arrangement of electrons amongst the quantum states of an atom as indicated by listing which of the atom's *quantum states* are occupied by its constituent electrons. The electronic structure can be written down using either the *standard notation* or the *box notation*. [*QPI*.3]

electron microscope A kind of microscope that uses *electrons* and electromagnetic lenses (rather than light and glass lenses) to form very highly magnified images. [*CPM*.1]

electron neutrino A kind of *elementary particle* that has no known substructure and is therefore regarded as a truly fundamental particle. It is the partner to the *electron* in the first *generation* of *leptons*. It has spin $\frac{1}{2}$, no charge and a mass of less than 0.000 015 MeV/c^2. [*QPM*.4]

electron number A dimensionless quantity that is conserved in all known interactions. The *electron* has an electron number of 1, and so has the *electron neutrino*. [*QPM*.4]

electron pairing The phenomenon that occurs in the *covalent bonding* of two atoms, whereby *electrons* that are unpaired in the separated atoms are shared to form a pair with opposite *spin* states in the bonded molecule. This electron pairing of *valence electrons* generally allows each atom to be surrounded by a closed *shell*, or closed *subshell*, of electrons. [*QPM*.2]

electronvolt A unit of *energy*, represented by the symbol eV and defined by the relation 1 eV = 1.602×10^{-19} J. The electronvolt is the change in *potential energy* of an electron that is displaced through a *potential difference* of 1 *volt*. [*SFP*.2; *QPM*.4]

electrophoresis A process in which a mixture of molecules or small particles suspended in a fluid is separated into its constituent components by applying a *potential* difference between two electrodes immersed in the fluid. The process makes use of the fact that the rate of movement of the molecules or particles depends on the *charge* they carry. [*SFP*.2]

electrostatic force The *force* that acts on a body due to its interaction with an *electric field*. In the case of a point particle of charge q, it is given by $\boldsymbol{F}_{\text{el}}$ (on q at $\boldsymbol{r}$) = $q\mathscr{E}(\boldsymbol{r})$, where $\mathscr{E}(\boldsymbol{r})$ is the electric field at the position $\boldsymbol{r}$ of the particle. The electrostatic force between two charges is described by *Coulomb's law*. [*SFP*.1]

electrostatic potential energy The *potential energy* of a particle or body that arises from its interaction with other particles or bodies via the (conservative) *electrostatic force*. The electrostatic potential energy of a charge q, placed at a point where the *electric potential* is V, is given by $E_{\text{el}} = qV$. [*SFP*.2]

electrostatic potential energy of two point charges (in free space) The *electrostatic potential energy* E_{el} of a point charge q_1 due to its electrostatic interaction with another point charge q_2, separated from it by a distance r in a vacuum, is

$$E_{\text{el}} = \frac{q_1 q_2}{4\pi\varepsilon_0 r},$$

where ε_0 is the *permittivity of free space* and, by convention, E_{el} is taken to be zero when $r = \infty$. [*SFP*.2]

electroweak theory A theory unifying the *electromagnetic* and *weak interactions*. The fact that the weak and electromagnetic interactions are actually different aspects of a single unified force is only expected to become manifest at very high energies. [*QPM*.4]

element Traditionally, a substance which cannot be divided by chemical means, heating or the passage of an electric current. More specifically, a sample of any given element consists of matter entirely composed of atoms with the same number of *protons* in their nuclei. [*CPM*.1]

elementary particle See *particle*.

elimination The process whereby a chosen variable that is common to two or more equations is removed from those equations, in order to produce a relationship between the remaining variables. [*DM*.1]

ellipse A closed curve shaped like a flattened circle. In Cartesian coordinates, the standard form of the equation of an ellipse centred on the origin is

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

where a and b are constants, called respectively the *semimajor axis* and the *semiminor axis*, that characterize a particular ellipse. The ellipse is a member of the family of curves known as *conic sections*. (See also *eccentricity* and *focus* (*of an ellipse*).) [*DM*.3]

elliptical orbit The most general path followed by one particle moving in a closed path around another due to their gravitational interaction. [*DM*.3]

emergence The proposal that some physical systems may display properties that could not be predicted on the basis of a complete knowledge of the underlying phenomena to which they might otherwise be reduced. (Most physicists would deny the truth of this in principle, but they would also accept it as effective in practice.) [*RU*.1]

EMF See *electromotive force*.

emission (of radiation) See *absorption*.

empirical Based on experimental observation.

emulsion (photographic) The photosensitive surface of photographic *film*; it consists of a layer of microscopic crystals of a *silver halide* suspended in a transparent gelatinous material. [*DFW*.3]

energy The property of a system that measures its capacity for doing *work*. The *SI* unit of energy is the *joule*, represented by the symbol J where 1 J = 1 N m. [*PM*.2]

energy bands The sets of closely spaced *energy levels*, occupied by *electrons* in *solids*, that are separated from one another by *energy gaps* according to the *band theory of solids*. [*QPM*.2]

energy density (at a surface) The energy falling perpendicularly on unit area of the surface. It is equal to the *intensity* of the radiation multiplied by the time of exposure. In the case of photographic film, the energy density at some point on the film is known as the *exposure* of the film at that point. [*DFW*.3]

energy distribution function Generally taken to be the same thing as the *translational energy distribution function*. [*CPM*.2]

energy distribution law for free electrons in metals See *Pauli's distribution*. [*QPM*.1]

energy distribution law for photons See *Planck's radiation law*. [*QPM*.1]

energy gaps See *energy bands*. [*QPM*.2]

energy histogram Generally taken to be the same thing as the *translational energy histogram*. [*CPM*.2]

energy levels These are the allowed energies of a particle in a quantum-mechanical system. If the particle is in a *bound* state, the energy levels are discrete. If the particle is not bound they form a continuum. Do not confuse energy levels with *quantum states*. [*QPI*.1]

entangled A term used to describe *states* and *wavefunctions* of systems, consisting of two or more parts, in which it is impossible to associate a particular wavefunction with one part of the system in isolation from the other parts. Such wavefunctions generally predict correlations between the results of measurements performed on different parts of the system, even when those parts are well separated, as in the case of the *Einstein–Podolsky–Rosen argument*. [*QPI*.4]

entropy A measure of the disorder of a *system*. The entropy S associated with a given *macroscopic equilibrium state* of a system is related to the number of microscopic *configurations* W which correspond to that state. The relationship is expressed by *Boltzmann's equation* $S = k \log_e W$, where the constant k is *Boltzmann's constant*. The *second law of thermodynamics* implies that the entropy of an *isolated system* is a *function of state*, that never decreases, so $\Delta S \geq 0$, the equality holding in the case of a reversible *adiabatic process*. (If a system is not isolated, ΔS may be positive or negative, but we may still say that $\Delta S_{\text{Univ}} \geq 0$, where the equality now holds for any *reversible process*.) The difference in entropy between two equilibrium states of a system may be evaluated by using the fact that the reversible transfer of an amount of *heat* Q_{rev} to a system at fixed *absolute temperature* T will increase the entropy of that system by an amount $\Delta S = Q_{\text{rev}}/T$. In the case of an *ideal gas* with *pressure* P and volume V, this implies that

$$S = nC_{P,\text{m}}\log_e\left(\frac{V}{V_0}\right) + nC_{V,\text{m}}\log_e\left(\frac{P}{P_0}\right) + S_0$$

where S_0 is the entropy of an arbitrarily chosen reference state with pressure P_0 and volume V_0. [*RU*.1; *CPM*.3]

environment The environment of a *system* is the rest of the *Universe*, not including the system. [*CPM*.3]

epilayers Very thin layers of one kind of crystalline material grown on top of another crystal. These layers may be the same except for a different *doping* or they may consist of totally different materials. [*QPM*.2]

equation of a circle An equation of the form $x^2 + y^2 = r^2$ that describes a circle of radius r, centred on the origin of a *Cartesian coordinate system*. [*DM*.3]

equation of a straight line An equation of the form $y = mx + c$, where m and c are constants that respectively represent the *gradient* and the *intercept* of the line. [*DM*.1]

equation of continuity The equation that describes the law of *conservation of mass* in an *ideal fluid*. [*CPM*.4]

equation of motion An equation that expresses (explicitly or implicitly) the position of a moving object as a function of time. Such equations often take the form of *differential equations* and are obtained by combining *Newton's second law of motion* with the *force laws* that are appropriate to the system under consideration. [*PM*.1]

equation of state An equation that relates the variables of *pressure*, volume and *temperature* for a *macroscopic system* in an *equilibrium state*. For an *ideal gas*, the equation of state is $PV = nRT$. [*CPM*.1; *CPM*.3]

equilibrium A system is said to be in a state of equilibrium if its measurable properties remain constant in time. [*RU*.1]

equilibrium position In the context of *simple harmonic motion*, the equilibrium position is the midpoint of that motion. [*DM*.3]

equilibrium separation The distance between two particles when they are in equilibrium. An example is the equilibrium distance between two *atoms* in a *diatomic molecule*. [*CPM*.1]

equilibrium state A settled and unchanging *state* of *thermodynamic equilibrium*. [*CPM*.3]

equipartition of energy theorem The assertion in *classical statistical mechanics*, that, in a system in *equilibrium* at *absolute temperature T*, each independent molecular *degree of freedom* contributes $kT/2$ to the average energy per molecule, where k is Boltzmann's constant. So, if a molecule has f degrees of freedom, its average energy will be $fkT/2$, as long as the equipartition theorem applies. [*QPI*.1; *CPM*.2]

equipotential A contour or surface connecting points of equal *electric potential*. Electric *field lines* always cut equipotentials at right angles. The equipotentials around an isolated point *charge* are concentric spheres centred on the charge. The concept may also be extended to other kinds of potential, such as *gravitational potential*. [*SFP*.2]

equivalent circuit A simple arrangement of circuit components in an electrical circuit that has the same effect as a more complicated arrangement. [*SFP*.3]

equivalent focal length See *effective focal length*. [*DFW*.3]

equivalent lens When two or more *thin lenses* are placed in contact (i.e. the separation between the lenses is negligible compared with their focal lengths), they can be treated as a single *equivalent lens* with a *focal length* f_{equiv}, given by $1/f_{\text{equiv}} = 1/f_1 + 1/f_2 + \ldots$, or an equivalent *power* P_{equiv}, given by $P_1 + P_2 + \ldots$. This latter format is very convenient in ophthalmology. [*DFW*.3]

escape speed The minimum speed with which a projectile must be launched if it is to escape completely from the Earth (or any other designated body). Ignoring *air resistance*, the escape speed from the Earth is given by

$$v_{\text{escape}} = \sqrt{\frac{2GM_{\text{E}}}{R_{\text{E}}}}$$

and is equal to $1.1 \times 10^4\,\text{m}\,\text{s}^{-1}$. [*PM*.2]

ether A hypothetical medium once supposed to permeate all of space and to be essential for the propagation of electrical and magnetic effects, including light, from one place to another. The concept of a material ether has been strongly disfavoured by physicists since the early twentieth century, partly as a result of the *Michelson–Morley experiment* of 1887. [*RU*.1; *DFW*.2; *DFW*.4]

Euler's equations The *equations of motion* of a rotating rigid body. They are usually written as *differential equations* relating the rates of change of the various components of the body's angular velocity, to the components of the net external *torque* that acts upon the body. [*PM*.4]

even function A function $f(y)$ that satisfies the condition $f(y) = f(-y)$ for all values of y. [*DM*.3]

event A physical occurrence of very short duration, which occurs in a very small region of space. Ideally it occurs at a point in space and at an instant in time. [*DFW*.4]

exchange particle A particle that, according to our current understanding, is responsible for one of the *fundamental forces*. In the context of *gauge theories*, they are also known as gauge bosons. [*QPM*.4]

excited states The states of a quantum system which have more energy than the *ground state*. In the context of an *atom*, the excited states correspond to energy levels of higher energy than the ground state energy level. [*QPI*.1]

expansivity The fractional increase in volume of a substance per unit increase in its *temperature*, under specified conditions (e.g. at constant *pressure*). [*CPM*.1]

exponential decay See *exponential process*. [*PM*.2]

exponential function A function that may be written in the form $v(t) = v_0 e^{\alpha t}$, where v_0 and α are constants. Any function of the form $y = a^x$, where a is a positive constant, may be written as $y = e^{kx}$ since it is always possible to find a constant k such that $e^k = a$, and we can then write $a^x = (e^k)^x = e^{kx}$. [*PM*.2]

exponential growth See *exponential process*.

exponential process A process of growth or decay that can be described by an *exponential function* $v(t) = v_0 e^{\alpha t}$. Exponential growth corresponds to a positive value of α, exponential decay to a negative value of α. In either case the process is characterized by the fact that the quantity v changes its value by equal factors in equal intervals of time, irrespective of when those intervals begin or end. A particularly well-known example is the decay of radioactive nuclei described by,

$$N(t) = N_0 \exp(-\lambda t)$$

where N_0 is the number of *parent nuclei* at $t = 0$, and the *decay constant* λ, the reciprocal of the *mean lifetime* τ, is related to the *half-life* $T_{1/2}$ by $T_{1/2} = \log_e(2)/\lambda$. [*PM*.2; *SFP*.3; *QPM*.3]

exposure (of photographic film) The product of the *intensity* I of the light falling on a given part of the film and the *exposure time* Δt; that is, exposure = $I\Delta t$. The exposure is a measure of the *energy density* of the light (i.e. the light energy per unit area) falling on that part of the film. [*DFW*.3]

exposure time (for photographic film) The time for which photographic film is exposed to the incident light. It can be adjusted by setting the *shutter-speed* on the *camera*. The total *exposure* at some point in the film plane is then given by the product of the *intensity* at that point and the exposure time. [*DFW*.3]

extended object An object that subtends a non-zero *visual angle* at the eye (or other optical system). It can be thought of as a connected collection of *point objects* located at progressively increasing distances from the *optical axis*. [*DFW*.3]

external force In the context of a given system, an external force is a force that acts on the system (or part of the system) but which has a reaction that acts outside of the system. [*PM*.3]

extrinsic semiconductor A *semiconductor* material that has been *doped* either to increase the number of *electrons* in the *conduction band*, making it an *n-type semiconductor*, or to increase the number of *holes* in the *valence band*, making it a *p-type semiconductor*. [*QPM*.2]

eyepiece The *eyepiece lens* in a *microscope* or *telescope*. [*DFW*.3]

eyepiece lens The *lens* in a *microscope* or *telescope* which is positioned next to the eye, often called just the *eyepiece*. [*DFW*.3]

factorization The mathematical process of writing an expression of the form $a_0 + a_1x + a_2x^2 + \ldots a_nx^n$ as a product of factors of the form $a_n(x - \alpha)(x - \beta)\ldots(x - \omega)$. For example, $ax^2 + bx + c$ can be written as $a(x - \alpha)(x - \beta)$, where the quantities α and β can be expressed in terms of a, b and c. [*DM*.2]

farad The *SI* unit of *capacitance*, represented by the symbol F, where $1\,\text{F} = 1\,\text{C}\,\text{V}^{-1}$. [*SFP*.2]

Faraday's law A law stating that; the magnitude of the *induced EMF* around the boundary of a surface is equal to the magnitude of the rate of change of the *magnetic flux* through that surface. In symbols

$$|V_{\text{ind}}(t)| = \left| \frac{d\phi(t)}{dt} \right|. \quad [DFW.1]$$

far point The most distant point on which the eye can clearly focus. For a 'normal' eye, it is at infinity (i.e. *rays* from this point are parallel as they enter the eye). [*DFW*.3]

far-point adjustment The condition in which a *magnifying glass*, *microscope* or *telescope* positions the final image (to be observed by the eye) at infinity (i.e. at the normal eye's *far-point*). The *angular magnification* is slightly greater in *near-point adjustment* than in far-point adjustment, but the eye is more relaxed in this latter adjustment. [*DFW*.3]

Feigenbaum constant A numerical constant, represented by the symbol δ, that arises in various ways in the study of *chaos*. In particular, in the limit where the periods of *limit cycles* are large, the intervals between successive period *doublings* get exponentially smaller as some parameter k increases, each interval being smaller than the previous interval by a factor δ, which has the value

δ = 4.669 201 609 102 990 671 853 203 820 466 201 617 258 185 577 475 768 632 745 651… [*PM*.5]

Fermi energy The energy E_F of the highest occupied state in a system of *fermions* in *thermal equilibrium* at 0 K. For a system of fermions in thermal equilibrium at temperature $T > 0$ K, the Fermi energy E_F is the energy at which the *Fermi occupation factor* equals $\frac{1}{2}$. [*QPM*.1]

Fermi level The boundary line on an energy-level diagram between filled states and unfilled states for a system of *fermions* in thermal equilibrium at 0 K. The Fermi level occurs at an energy equal to the *Fermi energy* E_F. [*QPM*.1]

Fermi occupation factor The factor

$$F_F(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

that determines the average number of particles in a single quantum state of energy E for a system of identical *fermions* in *thermal equilibrium* at *absolute temperature* T. The energy E_F that is a characteristic of the system is called the *Fermi energy*. [*QPM*.1]

Fermi speed The average speed of electrons near the *Fermi level*. The Fermi speed v_F is given, to a very good approximation, by $mv_F^2/2 = E_F$ where E_F is the *Fermi energy*. [*QPM*.2]

fermion A particle with odd half-integer spin (i.e. spin $\frac{1}{2}$, $\frac{3}{2}$, etc.). Fermions obey *Pauli's exclusion principle*. Consequently, only one fermion can occupy any given quantum state. [*QPM*.1]

ferromagnet A magnetic material that can become very strongly magnetized even in a relatively weak applied magnetic field. Examples are iron, cobalt, nickel and some associated alloys. [*SFP*.4]

Feynman diagram A diagram representing the interactions of particles in a *quantum field theory*. In conjunction with the appropriate *Feynman rules*, such diagrams can be used to predict physical quantities such as *cross-sections*. [*QPM*.4]

Feynman rules Procedures arising in quantum field theories that enable *Feynman diagrams* to be interpreted as mathematical expressions that can be used to predict physical quantities such as *cross-sections*. [*QPM*.4]

fictitious forces Forces with no basis in physical reality, but which can, nonetheless, be used to account for the motion of bodies observed from non-inertial *frames of reference*. By introducing such fictitious forces, the bodies can be made to conform to Newton's laws of motion, even though those laws do not, strictly speaking, apply in non-inertial frames. (See *centrifugal force* and *Coriolis force*.) [*PM*.1]

field A physical quantity to which a definite value can be ascribed at every point throughout some region of space. *Scalar fields* (e.g. temperature, pressure and *electric potential* fields) are specified by a scalar value at every point; *vector fields* (e.g. *electric fields*, *magnetic fields* and *gravitational fields*) are specified by a vector value at every point. Historically, fields were introduced into physics as a means of accounting for the propagation of forces and other measurable phenomena without having to admit the possibility of *action at a distance*. [*RU*.1; *SFP*.1]

field lines Lines used in pictorial representations of *vector fields*. They are directed along the field direction at every point and their spacing in any region indicates the magnitude of the field in that region: the closer together the lines, the stronger the field. *Electric field* lines emerge from positive charges and disappear into negative charges. Closed electric field lines can surround regions of changing magnetic flux. According to Maxwell's equations, *magnetic field* lines are continuous and have no beginning or end. However, outside a *permanent magnet*, magnetic field lines emerge from north poles and disappear into south poles. (To maintain continuity, the opposite is true inside the magnet, although this is not observed directly.) Closed magnetic field lines can surround electric currents and regions of changing electric flux. *Gravitational field* lines begin at infinity and terminate at masses. [*SFP*.1; *DFW*.1]

field of view The lateral extent of an object that can be satisfactorily imaged by an optical system. If the system has a large field of view, it means that it can accommodate an object that subtends a large *visual angle*, α_{OB}. [*DFW*.3]

film (photographic) A 'device' for recording photographic images; it consists of a photosensitive *emulsion* of suspended *silver halide* crystals deposited onto a transparent base material (typically a plastic polymer) for stability. [*DFW*.3]

fine structure A term used to describe the small energy splittings in atomic *energy levels* due to the interaction of the magnetic moments associated with the spin and the orbital behaviour of the electron — the so called *spin–orbit interaction*. [*QPI*.3]

first law of thermodynamics A law stating that; when a *system* undergoes a change from one *equilibrium state* to another, the sum of the *heat* transferred to the system and the *work* done on the system will depend only on the initial and final equilibrium states and not on

the *process* by which the change is brought about. This law justifies the introduction of a *function of state*, called the *internal energy*, that is conserved in any *isolated system*. It thereby provides the basis for the general principle of *conservation of energy* and is often represented by the equation $\Delta U = Q + W$. [*RU*.1; *CPM*.3]

fissile See *induced fission*. [*QPM*.3]

Fitzgerald–Lorentz contraction See *Lorentz contraction*. [*DFW*.4]

fixed target A term used to describe particle physics experiments in which a particle beam is directed at a stationary target. (Contrast with *colliding beams*.) [*QPM*.4]

fixer A chemical solution which when used on developed *film* renders the unexposed *silver halide* crystals soluble in water, thus enabling them to be removed from the film. [*DFW*.3]

fluid A sample of *matter* that is able to flow. Both *liquids* and *gases* are fluids. [*CPM*.3]

fluid dynamics The branch of *fluid mechanics* that concentrates on *fluids* that are moving, and the forces they exert on immersed *solid* objects. Fluid dynamics is also called hydrodynamics, even if the fluid involved is not water. [*CPM*.4]

fluid mechanics The branch of classical physics that investigates and predicts the behaviour of *fluids*, whether at rest or in motion. [*CPM*.4]

fluid statics The branch of *fluid mechanics* that studies *fluids* that are in a state of rest, and the forces they exert on immersed *solid* objects. Fluid statics is also called hydrostatics, even if the fluid involved is not water. [*CPM*.4]

fluoresce See *fluorescence*.

fluorescence A process by which atoms or molecules absorb energy, often in the form of radiation of a short wavelength (e.g. in the ultraviolet region of the spectrum) and re-emit it, usually, as radiation of longer wavelengths (e.g. in the visible region of the spectrum). Atoms undergoing this process are said to fluoresce. [*SFP*.3]

flywheel A heavy wheel of large *moment of inertia* used to store *rotational kinetic energy*. Flywheels are often used to smooth the output from engines. [*PM*.4]

***F*-number** The ratio of a lens's (or mirror's) *focal length f* to its *aperture diameter D*. [*DFW*.3]

focal length The distance between a *lens*'s *optical centre* and its *focal point* or, in the case of a *mirror*, the distance between its *focal point* and the point where the *optical axis* intersects the mirror's surface. For a *converging lens* or *converging mirror*, it is the distance over which parallel rays are brought to a focus. [*DFW*.3]

focal plane The plane that passes through a lens's or mirror's *focal point* and is perpendicular to its *optical axis*. [*DFW*.3]

focal point The point to which parallel rays striking a *converging lens* or *mirror* converge, or from which parallel rays striking a *diverging lens* or *mirror* appear to diverge. Also called the *principal focus*. [*DFW*.3]

focus (a) In the context of an *ellipse*; when the equation of the ellipse is written in the standard form, the foci of the ellipse are the two points lying on the x-axis, with x-coordinates $\pm ae$. [*DM*.3]

(b) In the context of an *optical system*; a focus is a point at which rays diverging from a single point are brought together again. (See also *focal point*.) [*DFW*.3]

forbidden transition A *radiative transition* is said to be forbidden if it corresponds to a change in *quantum numbers* that does not satisfy the relevant *selection rules*. Such transitions have a very low probability of occurring in comparison to *allowed transitions* which do satisfy the selection rules. [*QPI*.3]

force Informally, this is the amount of 'push' or 'pull' exerted on a *particle*, which, if unopposed, causes it to depart from the uniform motion predicted by *Newton's first law of motion.* It is, therefore, that which causes (or tends to cause) acceleration. It is a vector quantity, and so has both magnitude and direction. It is quantified by means of *Newton's second law of motion*, which says that the acceleration $\boldsymbol{a}$ of a particle is proportional to the *resultant force* $\boldsymbol{F}$ that acts on it, and inversely proportional to its mass m. Thus, in terms of vectors:

$$\boldsymbol{F} = m\boldsymbol{a}$$

or in terms of (scalar) components

$$F_x = ma_x, \quad F_y = ma_y, \quad F_z = ma_z$$

The *SI* unit of force is the *newton* (N). [*PM*.1]

force law A term used to describe any law that describes the magnitude and direction of a particular force under specified conditions. Examples include *Newton's law of universal gravitation*, the *law of terrestrial gravitation*, *Hooke's law*, *Coulomb's law* and the *Lorentz force law*. [*PM*.1]

formalism The mathematical aspects of a subject including equations, protocols and procedures for carrying out calculations and making predictions. [*QPI*.4]

forward bias The condition in which an external voltage is applied across a *p–n junction* so as to reduce the electric field in the *depletion layer* and increase the *diffusion current* flowing across it. In forward bias the positive terminal of the external voltage source is connected to the *p-type* material and the negative terminal to the *n-type*. [*QPM*.2]

fovea A tiny area in the eye, on the back of the *retina*, where the visual detectors are more densely packed than average. The most acute vision is achieved by focusing the image onto this area of the retina. [*DFW*.3]

fractal A self-similar pattern in which enlarging a small part of the pattern produces a new pattern that is similar to the original pattern. [*PM*.5]

fractional frequency The fraction of times a specified outcome occurs in a finite set of attempts. [*CPM*.2]

frame of reference A system of coordinate axes and synchronized clocks, that makes it possible to specify uniquely the location in space and time of any given event. [*PM*.1, *DFW*.4]

free-body diagram A diagram used in the analysis of mechanical systems that shows only a body of interest and the forces that act upon it. [*PM*.1]

free electrons A term used in modelling the behaviour of electrons in metals when the *valence electrons* that detach themselves from individual atoms are treated as moving freely throughout the volume of the metal without interacting with one another, or with the positive ions, apart from occasional collisions. The free electrons are also called *conduction electrons*. See *Drude's free-electron model* and *Pauli's quantum free-electron model*. [*QPM*.1]

free particle A particle for which the potential energy function $E_{pot}(x)$ is constant. A free particle therefore experiences no forces. [*QPI*.2]

free will The doctrine that human beings are free to determine their own actions. [*RU*.1]

frequency The rate at which *cycles* of a *periodic oscillation* are completed. For an oscillation of period T, the frequency is given by the reciprocal of the period; $f = 1/T$. The *SI* unit of frequency is the *hertz* (Hz), where $1\,\text{Hz} = 1\,\text{s}^{-1}$. The concept of frequency may also be extended to the case of *waves*, where a wave of period T is said to have a frequency $f = 1/T$. In this case the frequency represents the rate at which complete cycles of the wave pass a fixed point. [*DM*.3, *DFW*.2]

friction The phenomenon whereby a *force* (called a *frictional force*) acts on a body when it is in contact with another body (or with a viscous medium) and when there is relative motion, or a tendency for relative motion, between those bodies (or between the body and the medium.) [*PM*.1]

frictional force The force that arises when relative motion occurs or is tending to occur between two solid bodies that are in contact. Slightly different laws apply, depending on whether the object is moving or not. (See *coefficient of static friction* and *coefficient of sliding friction*.) [*PM*.1]

fulcrum The point at which a *lever* is supported; often coincident with a *pivot*. [*PM*.4]

function A term used to describe the mathematical relationship that exists between two variable quantities. y and x say, when the value of y depends on the value of x. The *dependent variable* y is said to be a function of the *independent variable* x and may be written as $y(x)$ to emphasize this dependence. The nature of any particular function is usually expressed in terms of an equation, such as $y = mx + c$, or $y = A\sin(kx)$, and may often be conveniently represented by means of a *graph* of y against x. [*DM*.1]

function of state The term used to describe any property of a *system* that depends only on the *equilibrium state* of the system, and not on how that equilibrium state was reached. Examples include *internal energy* and *entropy*. [*CPM*.3]

fundamental forces A term used when referring to the four known fundamental interactions: the *gravitational*, *weak*, *electromagnetic* and *strong interactions*. [*QPM*.4]

fundamental mode The mode of oscillation of a *standing wave* with the lowest possible *frequency*. In the case of a *wave* on a string, the fundamental mode has a *wavelength* equal to twice the length of the string. [*DFW*.2]

γ See *gamma*.

Galilean coordinate transformation The *coordinate transformation* of classical physics or Newtonian physics. If an *event* has coordinates (x, y, z, t) in *frame of reference* A, then the coordinates of the same event in frame of reference B, which is in *standard configuration* with A, are

$$x' = x - Vt,\ y = y',\ z = z' \text{ and } t = t',$$

where V is the relative speed of B with respect to A. Note that these equations are NOT CORRECT, and provide only an approximation to the *Lorentz transformation* at low speeds. (See also *velocity transformation*.) [*DFW*.4]

Galilean telescope A *refracting telescope* that uses a *diverging lens* as the *eyepiece* and a *converging lens* as the *objective*. (See also *telescope*.) [*DFW*.3]

Galilean velocity transformation See *velocity transformation*. [*DFW*.4]

γ-decay (gamma-decay) A type of radioactive *decay* process in which a *nucleus* spontaneously emits a *γ-ray*. This process often involves the decay of an excited *daughter nucleus* produced by a prior *α-decay* or *β-decay*. [*QPM*.3]

gamma factor See *Lorentz factor*. [*DFW*.4]

γ-rays *Electromagnetic radiation* with a *wavelength* shorter than around 10^{-11} m or a *frequency* greater than about 3×10^{19} Hz. A common source of such radiation is decaying *radioactive nuclei*. [*QPM*.3, *DFW*.2]

gas A phase of matter that has a low *density* and is able to flow and adopt the size and shape of any empty container. The *molecules* in gases have relatively large kinetic energies, and move around freely, occasionally colliding with one another or with the walls of their container. [*CPM*.1]

gauge pressure The *pressure* excess over atmospheric pressure, that would, for example, be registered by a suitably calibrated gauge carried by a diver. [*CPM*.4]

general relativity See *general theory of relativity*. [*DFW*.4]

general solution In the context of a *differential equation*, the general solution is a *function* that satisfies the equation and which contains a number of *arbitrary constants* equal to the *order* of the differential equation. An example is the general solution to the (second-order) *simple harmonic motion equation*; in this case the required function may be written as $x(t) = A\sin(\omega t + \phi)$, where A and ϕ are arbitrary constants that are determined by the initial conditions of the motion (ω is not an arbitrary constant since it appears in the simple harmonic motion equation). Subject to certain common conditions, any solution to a differential equation may be obtained from the general solution by making appropriate choices of the arbitrary constants. [*DM*.3, *PM*.1]

general theory of relativity The theory, published by Albert Einstein in 1916, that generalizes the ideas of his earlier *special theory of relativity* by extending them to non-*inertial frames of reference*. An important principle of the theory asserts that an accelerating *frame of reference* is locally equivalent to one that is located in a gravitational field. Consequently, the general theory of relativity is also a theory of gravitation, and as such supersedes Newton's theory of gravity. (The predictions

of Newton's theory approximate those of general relativity in situations where the gravitational fields are weak.) According to general relativity, gravity manifests itself in the geometric structure (curvature) of space-time. Mass and other sources of gravity determine that curvature, and moving bodies respond to that curvature, giving rise to the appearance of a 'gravitational force'. [*RU*.1, *DFW*.4]

generations Groupings of four fundamental *spin* $\frac{1}{2}$ particles that play an important role in the *standard model* of particle physics. According to the model there are three such generations, each of which contains two *quarks* and two *leptons*. The first generation consists of the *electron*, *electron neutrino*, *up quark* and *down quark* (or in symbols, e^-, ν_e, u, d). [*QPM*.4]

generic *PVT* surface A surface representing the sets of values of *pressure P*, volume *V* and *temperature T* that characterize the *equilibrium states* of a macroscopic sample of a typical pure substance. The surface is a pictorial representation of the *equation of state* of the substance and shows how different regions correspond to different phases (*solid*, *liquid* or *gas*) or combinations of phases. [*CPM*.1]

generic *UPT* surface A surface representing the sets of values of *internal energy U*, *pressure P* and *temperature T* that characterize the *equilibrium states* of a macroscopic sample of a typical pure substance. The surface is a pictorial representation of the *internal energy equation* of the substance and shows how different regions correspond to different phases (*solid*, *liquid* or *gas*) or combinations of phases. [*CPM*.1]

geostationary satellite A satellite that maintains a fixed position relative to any point on the Earth's surface. (See also *Clarke orbit*.) [*DM*.3]

gluon Any member of the family of eight spin 1 *exchange particles* that are, according to *quantum chromodynamics* (QCD), responsible for mediating the strong interaction. Gluons may be exchanged between *quarks* or between other gluons (but they have no direct connection with *leptons*). [*QPM*.4]

gradient of a graph The gradient of a *graph* of y (plotted vertically) against x (plotted horizontally) is a measure of how rapidly y changes in response to a change in x, at any point on the graph. If the graph is a straight line, then the gradient is the same at all points, and is given by the ratio $\Delta y/\Delta x$ where Δy is a change in y and Δx is the corresponding change in x. If the graph is a curved line, the gradient at any point P on the curve is defined as the gradient of the *tangent* to the curve at P. The gradient is also equal to the *derivative* of y with respect to x, $\mathrm{d}y/\mathrm{d}x$, evaluated at the point P. [*DM*.1]

grand unified theories (GUTs) *Quantum field theories* of the *fundamental interactions* that attempt to truly unify the *strong*, *weak* and *electromagnetic interactions* within a single theoretical framework. [*QPM*.4]

graph A representation of a *function* in pictorial form. In the case of a function $y(x)$, the usual procedure is to plot the values of y vertically and the values of x horizontally. [*DM*.1]

grating spacing The centre-to-centre separation of adjacent slits in a *diffraction grating*. [*DFW*.2]

gravitational constant See *law of universal gravitation.* [*SFP*.1]

gravitational field The gravitational field $\boldsymbol{g}(\boldsymbol{r})$ is a vector quantity that determines the *gravitational force* that would act on any mass placed at the point specified by the *position vector* $\boldsymbol{r}$. It is defined as the gravitational force per unit test mass, so if $\boldsymbol{F}_{\text{grav}}$ is the gravitational force on mass m at point $\boldsymbol{r}$, then $\boldsymbol{g}(\boldsymbol{r}) = \boldsymbol{F}_{\text{grav}}/m$. The gravitational field has both magnitude and direction at each point in space, so it is an example of a *vector field*, and gravitational fields due to different sources add vectorially at every point. For an important example of a gravitational field see *gravitational field due to a point mass.* At any point, the gravitational field component in a given direction is equal to minus the gradient of the *gravitational potential*, V_{grav}, in that direction. For example, the x-component and the radial component are given respectively by $g_x = -\mathrm{d}V_{\text{grav}}/\mathrm{d}x$ and $g_r = -\mathrm{d}V_{\text{grav}}/\mathrm{d}r$. The *SI* unit of gravitational field is $\mathrm{N\,kg^{-1}}$ or (equivalently) $\mathrm{m\,s^{-2}}$. [*SFP*.1, *SFP*.2]

gravitational field due to a point mass The *gravitational field* due to a *point mass* is spherically symmetric around the mass. If a mass M is placed at the *origin*, the *gravitational field* at a point specified by the position vector $\boldsymbol{r}$ is

$$\boldsymbol{g}(\boldsymbol{r}) = \frac{-GM}{r^2}\hat{\boldsymbol{r}}$$

where $\hat{\boldsymbol{r}}$ is a *unit vector* in the direction of $\boldsymbol{r}$ and G is the *universal gravitational constant*. Thus, the magnitude of the gravitational field depends only on the distance r from the point mass and is directed towards that mass. [*SFP*.1]

gravitational force The *force* that acts on a body due to its interaction with a gravitational field. In the case of a point particle of mass m, it is given by $\boldsymbol{F}_{\text{grav}}$(on m at $\boldsymbol{r}$) $= m\boldsymbol{g}(\boldsymbol{r})$, where $\boldsymbol{g}(\boldsymbol{r})$ is the gravitational field at the position $\boldsymbol{r}$ of the particle. The gravitational force between two point masses is described by the *law of universal gravitation.* [*SFP*.1]

gravitational interaction The fundamental interaction between all particles that possess mass. (Note that, according to the general theory of relativity, gravitational interactions also involve massless particles.) (See also *strong*, *weak* and *electromagnetic interaction.*) [*QPM*.4]

gravitational mass The mass of a body as determined by the relation $F_{\text{grav}} = GMm/r^2$. (Contrast with *inertial mass.*) [*PM*.1]

gravitational potential The gravitational potential $V_{\text{grav}}(\boldsymbol{r})$ at a point specified by the vector $\boldsymbol{r}$ is the *gravitational potential energy* per unit *mass* at that point. So, if E_{grav} is the gravitational potential energy of a mass m at a point $\boldsymbol{r}$, the gravitational potential at that point is

$$V_{\text{grav}}(\boldsymbol{r}) = \frac{1}{m}E_{\text{grav}}\ .$$

Gravitational potential has a scalar value at every point in space, so it is an example of a *scalar field*. The *SI* unit of gravitational potential is the $\mathrm{J\,kg^{-1}}$. An important example of a gravitational potential field is that due to a point mass M located at the origin of a coordinate system:

$$V_{grav} = -GM/r$$

where G is the universal gravitational constant and r is the distance from the point mass. Note that, by convention, the gravitational potential energy has been taken to be zero at $r = \infty$ in this case.

Another important example of a gravitational potential field is that close to the surface of the Earth:

$$V_{grav} = gh$$

where g is the magnitude of the acceleration due to terrestrial gravity and h represents height above the Earth's surface. Note that in this case the gravitational potential has been taken to be zero at the Earth's surface. [*SFP*.2]

gravitational potential energy The *potential energy* of a particle or body that arises from its interaction with other particles or bodies via the (conservative) *gravitational force*. A particular example is the potential energy associated with terrestrial gravitation, in which case $E_{grav} = mgh$, where m is the mass of the body, g is the magnitude of the *acceleration due to gravity*, and h is the height of the body above an arbitrarily agreed position of zero gravitational potential energy. Another important example is the potential energy of a body of mass m at a distance r from the centre of the Earth:

$$E_{grav} = -GM_E m/r,$$

where G is the *universal gravitational constant* and M_E is the mass of the Earth. More generally, the gravitational potential energy of a body of mass m, placed at a point where the gravitational potential is V_{grav}, is given by $E_{grav} = mV_{grav}$. [*PM*.2, *SFP*.2]

gravitational potential energy of two point masses The *gravitational potential energy* of a point mass m_1 due to its gravitational interaction with another point mass m_2, separated from it by a distance r is

$$E_{grav} = \frac{-Gm_1 m_2}{r}$$

where G is the *universal gravitational constant* and, by convention, E_{grav} is taken to be zero when $r = \infty$.

graviton A hypothetical *spin* 2 massless particle that occurs as the *exchange particle* in some attempts to formulate a quantum field theory of gravity. [*QPM*.4]

ground state The state that corresponds to the lowest discrete *energy level* of a quantum system. An example is the 1s state of the hydrogen atom. [*QPI*.1]

groups (a) In the context of *atoms*; groups are the vertical columns in the *Periodic Table* of the elements. The elements in a group are all characterized by the same outer-*shell electronic structure*. [*QPI*.3]

(b) In the context of *particle physics*; groups are mathematical structures that characterize certain *quantum field theories*. Well-known examples include SU(2) and SU(3). [*QPM*.4]

GUTs See *grand unified theories*. [*QPM*.4]

gyroscope A heavy, rotating disc mounted in such a way that it is free to rotate about its centre of mass. In the absence of external torques, the axis of the gyroscope maintains a fixed orientation in space; this causes the gyroscope to have important applications in the navigation and stabilization of ships, planes and space vehicles. [*PM*.4]

hadron resonance Any very short-lived *meson* or *baryon* with a *mean lifetime* of about 10^{-24} seconds. These particles live for too short a time for them to be directly observed, so their existence was first indicated by the presence of peaks in certain inelastic collision *cross-sections*; hence their peculiar name. [*QPM*.4]

hadrons A term used to refer collectively to *mesons* and *baryons*. Hadrons are composite particles that contain *quarks* and/or *antiquarks*, and which participate in strong interactions. Many types of hadron are known, including; *protons*, *neutrons*, *pions* and *kaons*. (Contrast with *leptons*.) [*QPM*.4]

half-life The time required for half of a given sample to decay when the relevant decay is an *exponential process*. (See *exponential process* and *mean lifetime* for further details.) [*QPM*.3]

Hall effect The effect whereby the application of a *magnetic field* perpendicular to a wafer of conducting material carrying a current along its length, causes a *potential difference* across the width of the wafer. Hall probes use this effect to measure the strength of magnetic fields. [*SFP*.4]

hard magnetic behaviour The behaviour of magnetic materials that retain much of their *magnetization* when the applied *magnetic field* responsible for that magnetization is removed. Such materials are generally difficult to magnetize, but the magnetization persists. [*SFP*.4]

harmonics The possible *standing waves* that can occur in a given system. For a string with fixed end-points, the first harmonic is the same as the *fundamental mode*. The second harmonic occurs when there are two half-wavelengths in the length of the string; the third occurs when there are three half-wavelengths in the length of the string, and so on. [*DFW*.2]

heat Any quantity of *energy* that is transferred as a direct result of a difference in *temperature*. According to one widely used convention, the symbol Q is used to represent heat that is transferred *to* a system *from* its environment. This convention implies that positive values of Q tend to increase the *internal energy* of the system. [*RU*.1; *CPM*.1; *CPM*.3]

heat bath Any enclosure at a controlled *temperature*, which can supply *heat* to a *system*, or absorb heat from it, without undergoing any appreciable change of temperature itself. [*CPM*.3]

heat capacity The quantity of *energy* per unit *temperature* rise needed to raise the temperature of a given body under specified conditions (such as constant *pressure* or constant volume). The *SI* unit of heat capacity is the $\mathrm{J\,K^{-1}}$. [*CPM*.3]

heat capacity at constant pressure The *heat capacity* of a body when its *pressure* is kept constant. [*CPM*.3]

heat capacity at constant volume The *heat capacity* of a body when its volume is kept constant. [*CPM*.3]

heat engine A device that converts *heat* into *work*. [*CPM*.3]

heating The process of transferring *heat* to or from a *system*. [*CPM*.1]

heavy damping The condition in which a *damped harmonic oscillator* is more than critically damped and consequently does not oscillate, but returns slowly to its equilibrium position. [*PM*.2]

Heisenberg's uncertainty principle A *quantum-mechanical* principle asserting that there is an inherent limit to the precision with which the values of certain pairs of physical quantities may be simultaneously known. It can be expressed in many forms, two of which are:

1 There is a fundamental limit to the precision with which the position x and the momentum component p_x of a particle can be simultaneously known. For any choice of x-axis, the product of the uncertainties Δx and Δp_x obeys the inequality $\Delta x\,\Delta p_x \geq \hbar/2$.

2 There is a fundamental limit to our knowledge of a particle's energy E, when it is measured in a finite time interval Δt: the uncertainty ΔE in the energy obeys the inequality $\Delta E\,\Delta t \geq \hbar/2$. [*QPI*.2; *QPM*.4]

heliocentric A term meaning 'Sun-centred', that is used to describe the theory propounded by Copernicus and others that the Earth and planets move around the Sun. By contrast, Ptolemy supported the 'Earth-centred' geocentric view that the Sun and planets move around the Earth. [*RU*.1]

Helmholtz pair A pair of identical conducting coils that are positioned coaxially with their centres separated by a distance equal to their radius. When the same current flows in the same sense through each, a *magnetic field* is produced which has a high degree of uniformity over a considerable region around the midpoint between the coils. [*SFP*.4]

henry The *SI* unit of *inductance* (both the *coefficient of self-inductance* and the *coefficient of mutual inductance*), represented by the symbol H, where $1\,\mathrm{H} = 1\,\mathrm{V\,s\,A^{-1}}$. [*DFW*.1]

hertz The *SI* unit of *frequency*, represented by the symbol Hz, where $1\,\mathrm{Hz} = 1\,\mathrm{s^{-1}}$. A *frequency* of 1 Hz is equivalent to one *cycle* per second. [*DM*.3; *DFW*.2]

hidden variables Hypothetical and currently unmeasurable physical variables that are supposed by some to account for our present need to use probabilities in an unavoidable way in *quantum mechanics*. *Bell's theorem* places strong constraints on viable hidden variable theories. *Bohm's theory* is a hidden variable theory that satisfies those constraints. [*QPI*.4]

Higgs boson A term used to describe any member of a class of hypothetical *spin* 0 elementary particles that play an important part in the *standard model* of particle physics. Higgs bosons are required by the standard model in order to account for some of the observed features of the combined *electromagnetic* and *weak interactions*; they also play a crucial role in determining particle masses. Higgs bosons are thought to be very massive (perhaps in excess of $200\,\mathrm{GeV}/c^2$). [*QPM*.4]

high-temperature superconductors (HTS) The *type II superconductors*, based on complex oxide structures, which have a *superconducting transition temperature* T_C much larger than was considered to be possible before 1986. The HTS title is most suitably applied to those materials with a T_C above 77 K, the boiling temperature of liquid nitrogen. [*QPM*.2]

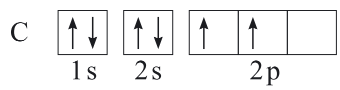
Hohmann transfer orbit A path, ideally part of an elliptical *orbit*, along which a space vehicle can travel from one planet to another with minimum expenditure of fuel. [*DM*.3]

hole A vacancy in an *energy band* of a *semiconductor* that behaves like a positively charged particle. When *electrons* are excited from the *valence band* into the *conduction band* or to *acceptor* levels in the semiconductor, there are empty states left in the valence band. When an electric field is applied to the semiconductor, electrons in the valence band can move into these empty states thereby allowing a current to flow. This movement of electrons in the direction opposite to the field direction is best described as the movement of positively charged holes, in the same direction as the field. In a *p-type semiconductor* the majority of charge carriers are holes. [*QPM*.2]

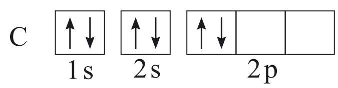
Hooke's law An empirical law stating that; when a body is stretched, the magnitude of the *restoring force* which opposes the stretching is directly proportional to the increase in the body's length. Hooke's law is not a fundamental law that must be obeyed by all bodies. Rather it describes the behaviour of some bodies, such as springs or elastic strings, provided they are not stretched too far. If a body is stretched along the x-axis, with x measuring the extension of the body, i.e. the displacement of the free end from its equilibrium position, then Hooke's law may be written in the form $F_x = -kx$ where k is the *force constant* of the restoring force. A spring that exactly obeys Hooke's law is said to be an *ideal spring*, and the force constant of such a spring is called the *spring constant* k_s. [*PM*.1]

horizon of predictability The number of iterations of an iterated *map* that must occur before a small change in the initial value leads to significant differences in the sequence of iterates. [*PM*.5]

Hund's rule A rule describing the order in which *quantum states* are filled in heavy atoms. It asserts that, in the *ground state* of an atom, the total spin of the electrons always has its maximum possible value (subject to the *Pauli exclusion principle*). This means that if two outer-*shell* electrons have several *degenerate* states available to them (corresponding to different values of m_l), they will have parallel spins and will therefore occupy states with different values of m_l. Thus, in carbon the *ground state electronic structure* is



and not



[*QPI*.3]

Huygens principle A principle asserting that; each point on a *wavefront* can be regarded as a source of secondary *waves*; in three dimensions these secondary waves are spherical; in two dimensions they are circular. The secondary waves from each point spread out equally in all directions with the wave speed v, just as ripples spread out across the surface of water when a stone is dropped into it. During an interval Δt, the individual secondary waves travel a distance $v\,\Delta t$ from each point on the wavefront. The new position of the wavefront at

the end of the interval is the envelope of these individual waves — a curve drawn tangentially through the individual secondary wavefronts. This new wavefront acts in turn as a further source of secondary waves, thus accounting for the continued propagation of the wave. [*DFW*.2]

hybrid state A *quantum state* of an *atom* with a *wavefunction* that is a *linear superposition* of the wavefunctions of states of different *angular momentum*. Important examples include the sp^3 hybrid states arising in atoms of carbon, silicon and germanium. Each of these atoms has four *valence electrons*, a single s electron and three p electrons. When these atoms bond to form molecules or solids, the wavefunctions of their four valence electrons can mix together to form four sp^3 hybrid states. In these states, all four electrons are unpaired and are available to make four *covalent bonds*. [*QPM*.2]

hydrogen bonding A kind of *bonding* that arises between *molecules* in which hydrogen atoms have formed *covalent bonds* with strongly *electronegative* atoms such as oxygen and fluorine. The bonding electrons are pulled towards the electronegative atom leaving the hydrogen end of the molecule with a positive charge. This makes the molecule a weak permanent *electric dipole* and allows the molecules to bond to one another with the negative end of one molecule linked to the positive hydrogen end of another by electrostatic attraction. Hydrogen bonding of this kind is important in ice. [*QPM*.2]

hypermetropia See *long-sightedness*. [*DFW*.3]

hyperopia See *long-sightedness.* [*DFW*.3]

ideal flow A state of steady flow in a *fluid* that has constant *density*, no *viscosity* and is free of eddies. [*CPM*.4]

ideal fluid A *fluid* that exhibits *ideal flow*. An ideal fluid is incompressible and has no *viscosity*, and its motion is steady and free of eddies. [*CPM*.4]

ideal gas A *gas* in which the molecular interactions play a completely negligible role. In equilibrium, an ideal gas obeys the *ideal gas equation of state* and *Joule's law for ideal gases*. [*CPM*.1]

ideal gas equation of state The equation

$$PV = nRT$$

which applies to a sample of *ideal gas* in *thermal equilibrium*, where P is the *pressure*, V the *volume*, n the quantity of gas (expressed in *moles*), T the (absolute) *temperature* and R ($= 8.314\,\mathrm{J\,K^{-1}\,mol^{-1}}$) the *molar gas constant*. [*CPM*.1]

ideal gas temperature scale A *temperature* scale based on the behaviour of *ideal gases*, and realized in practice by determining the behaviour of real *gases* in the limit of very low *pressures* where they obey the *ideal gas equation of state*. [*CPM*.1]

ideal spring A spring that produces a linear *restoring force* described by the *Hooke's law* relation, $F_x = -k_s x$, for all values of the extension x, irrespective of sign. Many real springs behave approximately like ideal springs provided they are not stretched or compressed too much. [*PM*.1]

image The spatial pattern of light produced by a *lens* or *mirror*, which is as accurate a reproduction as possible (apart from a scaling factor and a possible change of orientation) of the pattern distribution within the object. See *real image* and *virtual image*. [*DFW*.3]

image distance A signed quantity, usually represented by the symbol v, the magnitude of which is equal to the distance from a *lens* or *mirror* to the *image* produced by that lens or mirror. According to the *real-is-positive convention*, the image distance is positive for *real images* and negative for *virtual images*.

impact parameter In any scattering process, the impact parameter b is the length of the perpendicular drawn from the centre of the target to the original line of approach of the projectile. [*QPI*.1]

impulse The change of momentum produced when a given force (not necessarily constant) acts over a given time. If the force $\boldsymbol{F}$ is constant and it acts for a time interval Δt, then the impulse that it imparts will be $\boldsymbol{F}\,\Delta t$. [*PM*.3]

impulsive force A force that acts for a short time, such as the force between colliding rigid bodies. (See *impulse*.) [*PM*.3]

incoherent source A source in which different regions emit waves with significantly different *phases*. [*DFW*.2]

independent variable A quantity whose value can be chosen at will within specified limits. (See also *dependent variable* and *function*.) [*DM*.1]

indeterminacy The feature of *quantum mechanics* that implies the impossibility of having totally precise knowledge of all of the *observables* of a system at the same time. [*QPI*.4]

indeterminism The feature of *quantum mechanics* which implies that it is not generally possible to use knowledge of the precise value of an *observable* at some particular time to predict the precise value of that same observable at an arbitrary later time. [*QPI*.4]

indistinguishable The property of identical particles in quantum physics (two hydrogen atoms, for example) that prevents them from being labelled for the purposes of specifying and counting configurations. In quantum physics, identical particles are exactly alike and have no individual identity. [*QPM*.1]

induced current The electric current produced as a result of *electromagnetic induction*. An induced current may be produced as a result of the relative movement between a conducting wire and a *magnetic field*, or by a changing magnetic field. [*DFW*.1]

induced EMF The *EMF* produced as a result of *electromagnetic induction* in accord with *Faraday's law*. An induced EMF may be produced as a result of the relative movement between a conducting wire and a magnetic field, or by a changing magnetic field. [*DFW*.1]

induced fission A process in which an atomic *nucleus* is caused to split into two daughter nuclei by some external cause. Some heavy nuclei such as ^{235}U can absorb a *thermal neutron* and split into two roughly equal fragments with the release of energy and further neutrons. Such nuclei are said to be fissile. [*QPM*.3]

inductance See *coefficient of self-inductance* and *coefficient of mutual inductance*. [*DFW*.1]

induction (a) In the context of *electrostatics*; induction is the phenomenon whereby a charged object, brought close to an electrically neutral object (without touching it), will cause positive and negative charges in the neutral object to separate, leading to a net attraction between the charged object and the neutral one. (Contrast with *charge sharing*.) [*SFP*.1]

(b) In the context of *electromagnetism*; induction is the phenomenon whereby changing *magnetic flux* gives rise to an *induced EMF*. This phenomenon is more properly referred to as *electromagnetic induction*.

induction furnace A device for melting samples of metal, which is reliant on the *eddy currents* generated by *electromagnetic induction* within coils of wire. [*DFW*.1]

inductive circuit An electric circuit containing an *inductor*. When an *alternating current* is applied to the circuit, the phase of the voltage across an inductor leads the phase of the current through it by one-quarter of a cycle. [*DFW*.1]

inductor An element in an electrical circuit that has a significant *coefficient of self-inductance*. Inductors often take the form of a solenoid or a coil of wire. [*DFW*.1]

inelastic collision A collision in which *kinetic energy* is not conserved. [*PM*.3]

inelastic scattering A collision process in which the nature (or number) of the particles is changed. Inelastic scattering generally involves the conversion of kinetic energy into mass energy. [*QPM*.4]

inertia The phenomenon that causes a body to continue in its state of uniform motion (including the possibility of remaining at rest) unless acted upon by an unbalanced force. The mass of a body provides a measure of its inertia. (See *inertial mass*.) [*PM*.1]

inertial frame of reference An inertial frame of reference is a *frame of reference* in which any particle that is not acted on by an unbalanced force, moves with constant speed along a straight line. In other words, an inertial frame is a frame of reference in which Newton's first law is applicable. Any frame of reference that moves with constant velocity relative to an inertial frame of reference is also an inertial frame of reference. [*PM*.1; *DFW*.4]

inertial mass The mass of a body as determined by using *Newton's second law* via the relation $m = F/a$. (Contrast with *gravitational mass*.) [*PM*.1]

inertial observer An *observer* associated with an *inertial frame of reference*.

infrared radiation *Electromagnetic radiation* with a *wavelength* between about 7×10^{-7} m and 1×10^{-3} m, or a *frequency* between about 4×10^{14} Hz and 3×10^{11} Hz. [*DFW*.2]

initial conditions In the context of a *differential equation*, the initial conditions provide the information required to evaluate the *arbitrary constants* that arise in the *general solution* to the differential equation. For example, given a particle that moves in accordance with the simple harmonic motion equation, the general solution to that equation implies that $x = A\sin(\omega t + \phi)$, but in order to know exactly where the particle is at any given time it is necessary to determine the arbitrary constants A and ϕ. This can be done if the position and velocity of the particle are known at time $t = 0$; these are the initial conditions in this case. [*PM*.1]

initial phase See *phase constant*. [*DM*.3]

initial position The position of a particle at some chosen starting time, usually at $t = 0$. [*DM*.1]

in parallel A form of connection in electrical circuits. Two or more components, such as *resistors*, are said to be connected in parallel if one end of each is connected to a common point in the circuit while the other end of each is connected to some other common point, so that the *voltage* across each is the same. The effective *resistance* of a set of resistors connected in parallel is given by

$$\frac{1}{R_{\text{eff}}} = \sum_i \frac{1}{R_i}\,. \quad [SFP.3]$$

in series A form of connection in electrical circuits. Two or more components, such as *resistors*, are said to be connected in series if they are connected in a line so that the same *current* goes through each. The effective *resistance* of a set of resistors connected in series is given by

$$R_{\text{eff}} = \sum_i R_i\,. \quad [SFP.3]$$

instantaneous acceleration The *acceleration* of an object at a particular instant. See *acceleration*. [*DM*.1]

instantaneous speed The *speed* of an object at a particular instant. See *speed*. [*DM*.1]

instantaneous velocity (vector) The *velocity* of an object at a particular instant. See *velocity*. [*DM*.2]

instrumentalism A philosophical doctrine asserting that the purpose of a scientific theory can only be to predict the results of experiments. [*QPI*.4]

insulator (electrical) A material that conducts *electric currents* very poorly, or not at all. Insulators contain no free *charges* because all the electrons are bound to particular atoms of the material. (Insulators are also known as dielectrics.) In the context of the *band theory of solids*, insulators have an *energy gap* between the *valence band* and the *conduction band* of more than about 3 eV. There is no clear-cut distinction between an insulator and a *semiconductor* since the *electrical conductivity* depends on temperature. [*SFP*.1, *QPM*.2]

integral calculus The branch of mathematics concerned with the analysis and evaluation of (definite) integrals. [*PM*.2]

integration The mathematical process used in the evaluation of (definite) integrals. [*PM*.2]

intensity (of a wave) The amount of *energy*, carried by a wave, per unit time per unit area perpendicular to the direction of motion. It is proportional to the square of the *amplitude* of the wave. [*DFW*.2]

intercept The value on the vertical *axis* of a *graph* at which a plotted straight line crosses that axis, provided the vertical axis passes through the zero point on the horizontal axis. [*DM*.1]

interference The phenomenon arising from the *superposition* of two or more *waves* derived from an extended, but *coherent* source. (See also *constructive* and *destructive* interference.) [*DFW*.2]

interference fringes The bright and dark regions that make up the observed *interference* pattern caused by the *constructive* and *destructive interference* of two or more coherent waves. (See also *single-slit diffraction pattern* and *double-slit diffraction pattern*.) [*DFW*.2]

interferometer A device that can be used to measure lengths or changes in length (hence *speed*) very accurately by means of *interference* effects. (See also *Michelson–Morley experiment*.) [*DFW*.2]

internal energy The *energy* arising from the kinetic energy of the system's constituents and the potential energy of their mutual interaction. It does not include any contribution from the motion or position of the *system* as a whole. It is an equilibrium property of a *macroscopic* system that changes by an amount equal to the sum of the *heat* transferred to the system and the *work* performed on the system. In *thermodynamics*, it is represented by a *function of state*, U, that is conserved in any *isolated system*. In the case of a *monatomic ideal gas*, $U = 3nRT/2$, where n is the quantity of gas (in *moles*), R is the *molar gas constant*, and T is the *absolute temperature* of the gas. (See also *first law of thermodynamics*.) [*CPM*.1; *CPM*.3]

internal energy equation An equation that relates the *internal energy* to other *macroscopic* variables, such as volume and *temperature*, for a macroscopic *system* in an *equilibrium state*. (See also *internal energy* and *Joule's law of ideal gases*.) [*CPM*.1]

internal force In the context of a given system, an internal force is a *force* that acts within the system and which has a *reaction* that also acts within the system. [*PM*.3]

internal resistance The *resistance* of the chemicals and junctions inside a battery. The voltage supplied by the battery is given by $V = V_{EMF} - ir$, where V_{EMF} is the battery's *electromotive force*, i is the *current* drawn from the battery and r is the internal resistance of the battery. [*SFP*.3]

interpolation The process whereby the known values of a function, at certain points or in certain regions, are used to determine the approximate form of the function in other regions where its value may not be accurately known. The procedure is based on the assumption that the function varies smoothly between its known values — an assumption that may be seriously flawed in particular cases. Interpolation is often used (often intuitively) in graphical work. [*QPI*.3]

interpretation A detailed account of the physical significance of the various parts of the *formalism* of a subject. [*QPI*.4]

intrinsic semiconductor A pure *semiconductor* material that has not been *doped*. The number of *holes* in the *valence band* of an intrinsic semiconductor is equal to the number of thermally excited electrons in the *conduction band*. [*QPM*.2]

inverse square law A term used to describe any law asserting that the value of a quantity is proportional to the reciprocal of the square of some other quantity, usually the *distance* from some point. Well-known examples of inverse square laws include; *Coulomb's law*, *Newton's law of universal gravitation* and the law relating the *intensity* due to a *spherical wave* to the distance from the source of that wave. [*DM*.3; *PM*.1; *DFW*.2]

ion An *atom* that has become electrically charged, through having lost or gained one or more *electrons*. [*CPM*.1; *SFP*.2]

ionic bond A kind of *bonding* that arises between *atoms* and which can lead to the formation of individual *molecules* or solids. In an ionic bond, one or more *valence electrons* are transferred from one atom to a more strongly *electronegative* partner. The oppositely charged *ions* formed in this way are attracted electrostatically, thus creating the bond. The ionic bond is not *directional* and does not *saturate*. [*QPM*.2]

ionic solid A solid, such as sodium chloride, containing positive and negative ions held together by *ionic bonds* in a crystalline structure. [*QPM*.2]

iris The adjustable diaphragm in the human eye, located just in front of the *crystalline lens*, which gives the eye its characteristic hue. The hole at the centre of the iris, through which light enters the eye, is the eye *pupil*. [*DFW*.3]

irreversibility The characteristic of physical processes that prevents their time-reversed versions from occurring spontaneously. [*RU*.1]

irreversible process See *reversible process*. [*CPM*.3]

isobar (a) A line joining points in a *fluid* that are at the same *pressure*. [*CPM*.4]

(b) Any one of a set of *nuclei* that have the same value of the *mass number* A but different values of the *atomic number* Z. Nuclei connected by *β-decay* are isobars since β-decay does not change the value of A. [*QPM*.3]

isobaric expansivity The fractional increase in volume of a *system* when its *temperature* is increased at constant *pressure*. [*CPM*.1]

isolated system A *system* which cannot exchange *matter* or energy with its *environment*. In the context of *mechanics*, an isolated system is one that is subject only to *internal forces*. [*PM*.3; *CPM*.3]

isotherm A pathway on the *PVT surface* of a *system* (or on one of its projections, such as the *PV*-diagram) that represents an *isothermal process*. [*CPM*.3]

isothermal compressibility The fractional decrease in volume of a *system* when the *pressure* exerted on it is increased at constant *temperature*. [*CPM*.1]

isothermal condition The condition $PV = I$ that may be used to specify a particular *isothermal process* in a given quantity of *ideal gas*. The parameter $I = nRT$ will have a constant value for any particular isothermal process, but will have different values for isothermal processes that take place at different *temperatures*. [*CPM*.3]

isothermal process A *process* in which there is no change of *temperature*. (See also *isothermal condition*.) [*CPM*.3]

isotope Any one of a set of *atoms* that have the same value of the *atomic number* Z (and hence represent the same element), but different values of the *mass number* A (and hence different values of the *neutron number* N). The various isotopes of a given element thus represent different 'versions' of the atom of that element. The mass number and atomic number of an isotope are

indicated by writing them as a superscript and subscript, respectively, before the relevant chemical symbol. For example, the isotope of silicon with $A = 27$ and $Z = 14$ is written ${}^{27}_{14}\mathrm{Si}$. Less formally, this isotope may be referred to as silicon-27. [*CPM*.1; *QPI*.3; *QPM*.3]

iteration A procedure in which a rule is used to generate a sequence of results by using the output from one application of the rule as all or part of the input to another application of the same rule. [*PM*.5]

Josephson junction A device consisting of two pieces of *superconductor* separated by a very thin layer of *insulator*. *Cooper pairs* are able to *tunnel* through the insulator and pass between the superconductors. The insulator is usually an oxide coating that is just a few molecules thick. The current through a superconducting Josephson junction can be controlled to provide very fast low-power switching, which may eventually find applications in large computers. [*QPM*.2]

joule The *SI* unit of *energy* and of *work*, represented by the symbol J, and defined by the relation $1\,\mathrm{J} = 1\,\mathrm{kg\,m^2\,s^{-2}} = 1\,\mathrm{N\,m}$. [*PM*.2]

Joule's classification The proposal by James Joule that, for the purpose of calculating the *pressure* of a *gas*, it would make no difference if we imagined dividing the *molecules* into three classes: one-third moving to and fro along the x-axis, one-third moving to and fro along the y-axis and one-third moving to and fro along the z-axis. [*CPM*.2]

Joule's law of ideal gases A law stating that; the *internal energy* of an *ideal gas* is independent of *pressure* or volume. [*CPM*.1]

kaon A kind of *elementary particle*. A *spin* 0 *meson* with approximately half the mass of a *proton*. There are four kinds of kaon, denoted K^+, K^-, K^0, $\overline{K}^0$ according to charge (and strangeness). Kaons were the first *strange particles* to be discovered. [*QPM*.4]

kelvin The *SI* unit of *temperature* and temperature difference, represented by the symbol K. The kelvin is one of the seven SI *base units*, and is defined as 1/273.16 of the *absolute temperature* of the triple point of H_2O. A temperature difference of one kelvin (1 K) is equivalent to a temperature difference of one degree Celsius (1 °C), but the absolute and Celsius scales have different origins. [*CPM*.1]

Kelvin's statement of the second law of thermodynamics The statement that; no *cyclic process* is possible which has, as its sole result, the complete conversion of a positive quantity of *heat* into *work*. [*CPM*.3]

Keplerian telescope A *refracting telescope* that uses *converging lenses* for both the *eyepiece* and the *objective*. (See also *telescope*.) [*DFW*.3]

Kepler's laws Three empirical laws, deduced by Johannes Kepler, that approximately describe the motion of the planets around the Sun. The laws state that;

1 The orbit of each planet is an *ellipse* with the Sun at one *focus*.

2 A radial line from the Sun to a planet sweeps out equal areas in equal intervals of time.

3 The square of the orbital *period* of each planet is proportional to the cube of its *semimajor axis*.

Kepler's laws will hold for other planetary systems as well as the Sun's, but the constant of proportionality in the third law will differ from one system to another. [*DM*.3]

kilo A prefix used to indicate the standard *SI multiple* of 10^3. [*DM*.1]

kilogram The *SI* unit of mass, represented by the symbol kg. The kilogram is one of the seven SI *base units*, and is defined by a manufactured standard kilogram kept in France. [*PM*.1]

kilowatt hour A unit of *energy*, represented by the symbol kW h, and defined by the relation

$$1\,\mathrm{kW\,h} = 1\,\text{kilowatt} \times 1\,\text{hour} = 3.6\,\mathrm{MJ}.$$

The kilowatt hour is widely used in billing for electrical energy. [*PM*.2; *SFP*.3]

kinematics The branch of *mechanics* concerned with motion and its description, but not its causes. [*DM*.1; *PM*.1]

kinetic energy The *energy* that a body possesses by virtue of its motion. See *translational kinetic energy* and *rotational kinetic energy*. [*RU*.1; *PM*.2]

kinetic theory of gases A theory that accounts for the behaviour of *gases* in terms of the movement of the molecules of which the gas is composed. [*CPM*.2]

Kirchhoff's laws Two laws, introduced by Gustav Kirchhoff, that describe the flow of steady direct currents in electrical circuits. The laws state that:

1 The sum of the potential changes in a given sense around a circuit is zero. (In this sum, a potential drop is taken as negative and a potential rise as positive.)

2 At a junction of two or more wires, the current flowing into the junction is equal to the current leaving the junction. [*SFP*.3]

lambda particle A kind of *elementary particle*. A *strange baryon* with *spin* $\frac{1}{2}$, and a mass that is about 20% greater than that of the proton. The lambda particle is electrically neutral and is represented by the symbol Λ^0. [*QPM*.4]

laser A device that uses the phenomenon of *stimulated emission* to amplify a light wave, producing an intense, *coherent* source of light in the form of a narrow beam. The word 'laser' is an acronym for Light Amplification by the Stimulated Emission of Radiation. [*QPI*.3]

law of conservation of angular momentum See *conservation of angular momentum*. [*PM*.4]

law of conservation of energy See *conservation of energy*. [*RU*.1; *PM*.2]

law of conservation of linear momentum See *conservation of linear momentum*. [*PM*.3]

law of conservation of mass See *conservation of mass*. [*RU*.1]

law of conservation of mechanical energy See *conservation of mechanical energy*. [*PM*.2]

law of reflection A law stating that; when a *wave* strikes a reflecting surface, the incident and reflected *rays* and the normal to the reflecting surface all lie in the same plane, and the *angle of incidence* equals the *angle of reflection*, i.e. $i = R$. [*DFW*.2]

law of refraction A law stating that; when a *wave* travels from one medium in which its *speed* is v_1 to another in which its speed is v_2 (such that $v_1 \neq v_2$), the *angle of incidence* i and the *angle of refraction* r are related by:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

where n_1 and n_2 are the *refractive indices* of the two media. This law is also known as *Snell's law*. [*DFW*.2]

law of terrestrial gravitation A law stating that; at any location on Earth, all objects that are subject only to the effect of gravity have the same downward acceleration $\boldsymbol{g}$, irrespective of their mass and composition. In *Newtonian mechanics*, a direct consequence of this law is that close to the Earth's surface, any body of mass m experiences a gravitational *force* (the body's *weight*) which acts vertically downwards and has magnitude mg, where g is the magnitude of the *acceleration due to gravity* (approximately $9.81\,\mathrm{m\,s^{-2}}$). [*PM*.1]

law of universal gravitation A law stating that; every particle of matter attracts every other particle of matter with a *gravitational force*, whose magnitude is directly proportional to the product of the masses of the particles, and inversely proportional to the square of the distance between them. It follows from this that, if a particle of mass m_1 is separated by a distance r from a second particle of mass m_2, then the gravitational force on the second particle due to the first is directed towards the first particle and has magnitude

$$F_{21} = \frac{Gm_1m_2}{r^2},$$

where $G = 6.673 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}}$ is the *universal gravitational constant*. By introducing a dimensionless unit vector $\hat{\boldsymbol{r}} = \boldsymbol{r}/r$ parallel to the displacement vector $\boldsymbol{r}$ from the first particle to the second, the force on the second particle, due to the first, may be written

$$\boldsymbol{F}_{21} = \frac{-Gm_1m_2}{r^2}\hat{\boldsymbol{r}}.$$ [*PM*.1; *SFP*.1]

***LC* circuit** An electrical circuit consisting of an *inductor* and a *capacitor*. Such circuits support charge oscillations at a *natural frequency* $f = 1/2\pi\sqrt{LC}$, where L is the *inductance* and C the *capacitance*. When an LC circuit is driven by an externally supplied signal, its response will be greatest when the frequency of the driving signal is close to the natural frequency of the LC circuit. This provides the basis for the *tuned circuits* used in radio and television receivers. (See also *inductive circuit* and *capacitive circuit*.) [*DFW*.1]

length contraction See *Lorentz contraction*. [*DFW*.4]

lens A device (usually a specially shaped piece of glass, or other material with a *refractive index* different from that of its surroundings) that is able to convert plane *wavefronts* into spherical wavefronts or, equivalently, make incident parallel *rays* converge to a point or appear to have diverged from a point. (See also *converging lens* and *diverging lens*.) [*DFW*.3]

lens equation The equation

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

that relates the *object distance* u, the *image distance* v and the *focal length* f of a *thin lens*. (The equation also holds true for curved mirrors.) In the *real-is-positive convention*, the focal length of a *converging lens* or *mirror* is positive, that of a *diverging lens* or *mirror* is negative; *real images* and *real objects* are positive, and *virtual images* and *virtual objects* are negative. [*DFW*.3]

Lenz's law A law stating that; when a changing *magnetic flux* generates an *induced EMF*, the effect of that EMF is to oppose the change that caused it. Although Lenz's law, like *Faraday's law*, is phrased in terms of EMFs, the induced EMF will, in general, give rise to an *induced current*, which in turn will give rise to a *magnetic field*. It is usually the effect of this (induced) magnetic field that needs to be considered when working out the direction in which the induced current will flow. [*DFW*.1]

lepton number A dimensionless quantity that is conserved in all known interactions. It is usually given the symbol L and all *leptons* (and *antileptons*) have non-zero lepton number. Now regarded as the sum of the *electron number*, *muon number* and *tauon number*, the lepton number of the *electron* and the *electron neutrino* is $L = 1$, while that of the *positron* is $L = -1$. [*QPM*.4]

leptons Fundamental particles of spin $\frac{1}{2}$ that do not participate directly in *strong interactions*, though they may interact via the *weak* or, if charged, the *electromagnetic interaction*. Only six types of lepton are known; *electrons*, *electron neutrinos*, *muons*, *muon neutrinos*, *tauons* and *tauon neutrinos* (or, in terms of symbols, e^-, ν_e, μ^-, ν_μ, τ^-, ν_τ). [*QPM*.4]

lever A rigid beam, supported at one point by a *fulcrum*, about which it can turn. [*PM*.4]

lifetime (against spontaneous emission) The *time constant* τ that characterizes the spontaneous decay of an *atom* in a specified *excited state*. Decay to a lower *energy level* occurs in a random fashion and in such a way that that if there are N_0 atoms in a given excited state at time t then the number remaining in that state at time $t + \tau$ will be, on average, N_0/e. [*QPI*.3]

lift A *force* that acts on a body moving through a *fluid*. Lift is perpendicular to the body's direction of motion and arises from the difference in pressure across the body due to *Bernoulli's principle*. [*CPM*.4]

light See *visible light*. [*DFW*.2]

light clock An idealized clock in which a pulse of light bounces back and forth between two parallel mirrors, with the clock 'ticking' every time the light pulse hits either one of the mirrors. Although this would be a pretty impractical clock in real life, it has the advantage that time intervals, as measured by a light clock, depend only on the principle of the constancy of the *speed of light*, and can therefore be interpreted unambiguously using Einstein's *special theory of relativity*. [*DFW*.4]

light damping The condition in which a *damped harmonic oscillator* is less than *critically damped* and

consequently only returns to its *equilibrium position* after completing several *oscillations*. [*PM*.2]

light-emitting-diode (LED) A *p–n junction* device under *forward bias* that produces light via the *recombination* process, when *electrons* and *holes* meet in the *depletion region*. The *photons* produced typically have an energy equal to that of the *semiconductor energy gap*. [*QPM*.2]

light-gathering power A measure of the extent to which a *telescope* can increase the apparent brightness of an object (relative to its brightness when viewed directly by eye) by collecting the light over a large area and concentrating it into an area less than or equal to the area of the eye *pupil*. For a telescope with an *objective aperture diameter* of D_o and set up in *far-point adjustment*, the light-gathering power is given by $(D_o/D_p)^2$, where D_p is the diameter of the eye pupil. (This assumes that the diameter of the 'exit beam' at the eyepiece lens is less than or equal to D_p, so that all the light leaving the telescope can enter the eye.) [*DFW*.3]

limit cycle A mode of behaviour in which the sequence of values arising from the *iteration* of a *map* settles down to an oscillation that repeats itself after a certain number of steps. [*PM*.5]

linac See *linear accelerator*. [*QPM*.4]

line See *equation of a straight line*.

linear accelerator A type of *particle accelerator* in which charged particles are accelerated in a straight line. It is also known as a *linac*. [*QPM*.4]

linear function A *function* of the form $f(x) = Ax + B$, where A and B are constants. [*DM*.1]

linear magnification A measure of the enlargement in the size of the *image* produced by a *lens* or *mirror* relative to the size of the object. It can be calculated from the equation $m = v/u$, where v is the *image distance* and u the *object distance*. If the image size is less than the object size, m will be less than 1 but greater than 0. [*DFW*.3]

linear map A rule for turning one set of values into another that could form the basis of a *linear function*. [*PM*.5]

linear momentum The *momentum* associated with the *translational motion* of a body. For a *particle* of *mass m* travelling with *velocity* $\boldsymbol{v}$, the linear momentum is

$$\boldsymbol{p} = m\boldsymbol{v}.$$

For a *rigid body* of mass M,

$$\boldsymbol{p} = m\boldsymbol{v}_{\text{CM}}.$$

where $\boldsymbol{v}_{\text{CM}}$ is the velocity of the body's *centre of mass*. (See also *conservation of linear momentum*, and *relativistic momentum*.) [*PM*.3]

linear restoring force A *force* tending to return an object to some former position, with the property that its *magnitude* is proportional to the *displacement* from that position. [*PM*.1]

linear superposition Given n functions Ψ_1, Ψ_2, Ψ_3, … Ψ_n, their linear superposition is any expression of the form

$$\Psi = c_1\Psi_1 + c_2\Psi_2 + c_3\Psi_3 + \ldots + c_n\Psi_n$$

where c_1, c_2, c_3, etc. are numbers, which may generally be complex numbers. (See also *principle of superposition*.) [*QPI*.4]

linear system A *system* that is described by a *linear map* or a linear *equation of motion*. [*PM*.5]

line of action A line that passes through the point of application of a force, and is parallel to the direction in which the force acts. [*PM*.1]

liquid A phase of *matter* that is able to flow, but does not expand to fill the whole volume of any empty container. The liquid phase of any substance is generally denser than the corresponding gas phase. The *molecules* in liquids exhibit *short-range order* and move around mainly in the vicinity of their neighbours, but occasionally take longer jumps to join other groups of molecules. [*CPM*.1]

locality The characteristic of a physical theory which implies the absence of faster than light connections that would enable a result obtained at one point at time t, to influence a result obtained at any other point, a distance d away, at any time earlier than $t + d/c$. [*QPI*.4]

logarithmic function See *logarithm to the base e*. [*PM*.2]

logarithm to the base e Given a positive number x, its logarithm to the base e is the power to which e must be raised to obtain the given number. So if $x = \text{e}^y$ then we say that y is the log to the base e of x, and we write $y = \log_e x$. In the case where x is a positive *variable*, it is possible to define a logarithmic function using the relationship, $f(x) = \log_e x$. The logarithmic function is the inverse of the *exponential function*, since $\log_e \text{e}^y = y$. The idea of a logarithm and of a logarithmic function may be extended to bases other than e, though logarithms to the base e are known as natural logarithms. [*PM*.2]

logistic map A non-linear rule (for turning one set of values into another) that may be written in the form, $x_{n+1} = kx_n(1 - x_n)$. [*PM*.5]

longitudinal wave A *wave* composed of *oscillations* that take place in a direction parallel to the *direction of propagation* of the wave. (Contrast with *transverse wave*.) [*DFW*.2]

long-range order The phenomenon exhibited by some forms of matter, particularly *crystalline solids*, in which the neighbours of a typical atom show signs of regularity and order in their spatial arrangement, and that order extends even to quite distant neighbours. A line of *atoms*, for instance, in which the interatomic spacing remains constant over many atoms, clearly displays long range order. (Contrast with *short-range order*, and see also *radial density function*.) [*CPM*.1]

long-sightedness A defect of vision in which the *near point* of the eye is considerably further away than the *normal near point* of 250 mm (and the *far point* 'beyond infinity'). As a result the eye is unable to focus on near objects (the eye is too weak, and light from an object located at the *normal* near point would be focused beyond the back of the eyeball). Long-sightedness is known technically as *hyperopia* or *hypermetropia*. [*DFW*.3]

Lorentz contraction A phenomenon arising in Einstein's *special theory of relativity*, often summed up by the statement 'moving rods contract in the direction

of their motion'. If the length of a rod is recorded as L_0 in a *frame of reference* in which the rod is at rest, then the length of the same rod, measured from a frame of reference in which the rod is moving at speed V in a direction parallel to the original measurement, has the contracted value

$$L = L_0\sqrt{1-\frac{V^2}{c^2}}.$$

Lorentz contraction is built into the *Lorentz transformation*. [*DFW*.4]

Lorentz factor The factor $\dfrac{1}{\sqrt{1-\dfrac{V^2}{c^2}}}$ which occurs often in equations relating to the *special theory of relativity*. It is represented by the symbol γ (gamma) and is dimensionless. (See also *Lorentz transformation*, *time dilation*, *Lorentz contraction*, *velocity transformation*, *relativistic energy* and *relativistic momentum*.) [*DFW*.4]

Lorentz force law A law stating that; a particle of *charge* q, moving with *velocity* $\boldsymbol{v}$ at a point specified by the position vector $\boldsymbol{r}$, is subject to a force

$$\boldsymbol{F} = q[\mathscr{E}(\boldsymbol{r}) + \boldsymbol{v}\times\boldsymbol{B}(\boldsymbol{r})]$$

where $\mathscr{E}(\boldsymbol{r})$ and $\boldsymbol{B}(\boldsymbol{r})$ are, respectively, the *electric* and *magnetic fields* at the point $\boldsymbol{r}$. [*SFP*.4]

Lorentz transformation The *coordinate transformation* of *special relativity*. If an *event* has *coordinates* (x, y, z, t) in *frame of reference* A, then the coordinates of the same event in frame of reference B, which is in *standard configuration* with A, are

$$x' = \frac{x - Vt}{\sqrt{1-V^2/c^2}}$$

$$y' = y$$

$$z' = z$$

$$t' = \frac{t-(Vx/c^2)}{\sqrt{1-V^2/c^2}}$$

where V is the relative speed of B with respect to A. An approximation to the Lorentz transformation at low speeds is provided by the *Galilean coordinate transformation*. (See also *velocity transformation*.) [*DFW*.4]

macroscopic A term used to indicate that the relevant size scale is moderately large. For example, a *system* is said to be macroscopic if it is sufficiently large for its bulk characteristics to be easily measured. Macroscopic systems are normally larger than 0.1 mm across and contain more than 10^{17} *atoms*. (Contrast with *microscopic*.) [*CPM*.1]

magic nuclei See *magic numbers*. [*QPM*.3]

magic numbers There are more stable nuclei with either the *atomic number* Z or *neutron number* N equal to one of the numbers 2, 8, 20, 28, 50, 82 and 126, than might be expected. These nuclei are called magic nuclei. The numbers are called magic numbers and can be understood in the context of the *nuclear shell model*. [*QPM*.3]

magnetic bottle A non-uniform *magnetic field* configuration that may be used to trap charged particles, especially those in a *plasma*. [*SFP*.4]

magnetic dipole Any system that produces a *magnetic field* similar to that of an infinitesimally small bar magnet. A compass needle is a good approximation to a magnetic dipole. Any magnetic dipole experiences a torque in a *magnetic field* unless it is oriented parallel or antiparallel to the field. The magnitude of the torque depends on the strength of the applied magnetic field and a quantity called the magnetic dipole moment that characterizes the magnetic dipole. [*SFP*.4]

magnetic energy The *energy* associated with a given distribution of *electric currents*. This energy is often regarded as being 'stored' in the *magnetic field* created by the currents. In the case of a current carrying *inductor*, the magnetic energy is $E_{\text{mag}} = \frac{1}{2}Li^2$, where i is the current in the inductor, and L is the *coefficient of self-inductance*. (Contrast with the *electrical energy* of a capacitor.) [*DFW*.1]

magnetic field The vector quantity $\boldsymbol{B}(\boldsymbol{r})$ that determines the *magnetic force* that would act on any charged particle as it moves through the point specified by the *position vector* $\boldsymbol{r}$. It is defined by the requirement that the magnetic force $\boldsymbol{F}_{\text{m}}$ on a particle of *charge* q moving with *velocity* $\boldsymbol{v}$ as it passes through the point $\boldsymbol{r}$ is given by $\boldsymbol{F}_{\text{m}} = q[\boldsymbol{v} \times \boldsymbol{B}(\boldsymbol{r})]$. The magnetic field has both magnitude and direction at each point in space, so it is an example of a *vector field*, and magnetic fields due to different sources add vectorially at every point. An important example of a magnetic field is that due to an infinitely long, straight wire carrying a steady current i, in which case the magnetic field at a distance r from the wire acts in the plane perpendicular to the wire (in the direction specified by the *right-hand grip rule*) and has magnitude

$$B(r) = \frac{\mu_0 i}{2\pi r}$$

where μ_0 is the *permeability of free space*. Other important examples include the magnetic field at the centre of a single coil of radius R, carrying a steady current i (in which case the magnitude is $B_{\text{centre}} = \mu_0 i/2R$), and the field along the axis of an infinitely long cylindrical solenoid with N/l turns per unit length (in which case the magnitude is $B = \mu_0 Ni/l$). The *SI* unit of magnetic field is the *tesla*, represented by the symbol T, where $1\,\text{T} = 1\,\text{kg}\,\text{s}^{-2}\,\text{A}^{-1}$. (See also *magnetic field strength*.) [*SFP*.4]

magnetic field strength The magnitude of the *magnetic field*. A particle of *charge* q moving with speed v at an angle θ to a magnetic field of strength B experiences a force of magnitude $F_{\text{m}} = |q|vB\sin\theta$. This equation can be used to interpret the *SI* unit of magnetic field, the *tesla* (T), where $1\,\text{T} = 1\,\text{N}\,\text{s}\,\text{m}^{-1}\,\text{C}^{-1}$. A magnetic field of strength 1 T exerts a force of 1 N on a particle of charge 1 C moving perpendicularly to it at a speed of $1\,\text{m}\,\text{s}^{-1}$. The magnetic field strength near a typical bar magnet is of order of 10^{-1} T; large superconducting magnets produce magnetic field strengths of several hundred tesla. The magnitude of the Earth's magnetic field, measured at the surface, is of the order of 10^{-5} T. [*SFP*.4]

magnetic flux A measure of the extent to which a given *magnetic field* 'passes through' a given surface. In the case of a uniform magnetic field and a flat surface, the flux through the surface is $\phi = AB\cos\theta$, where A is the area of the surface, B is the magnitude of the magnetic field and θ is the angle between the *normal* to the surface and the direction of the magnetic field. Alternatively, the magnetic flux is given by the *scalar product* $\phi = \boldsymbol{A} \cdot \boldsymbol{B}$, where $\boldsymbol{A}$ is a vector perpendicular to the surface with a magnitude equal to the area of the surface, and $\boldsymbol{B}$ is the magnetic field. The magnetic flux through a solenoid consisting of N turns of wire may be written $\Phi = NAB = N\phi$, where N is the number of turns on the solenoid, and ϕ is the magnetic flux through a single turn. The total magnetic flux through any closed surface will always be zero (a fact that is related to the non-existence of *magnetic monopoles*). Magnetic flux is measured in the *SI* unit of *weber* (Wb). The concept of *flux* may be generalized to non-magnetic situations; for instance, considering an electric field rather than a magnetic field leads to the idea of electric flux, which is also of some use in electromagnetism. [*DFW*.1]

magnetic force The *force* that acts on a body due to its interaction with a *magnetic field*. In the case of a point particle of *charge* q moving with velocity $\boldsymbol{v}$, the magnetic force is given by $\boldsymbol{F}_{\mathrm{m}} = q(\boldsymbol{v} \times \boldsymbol{B}(\boldsymbol{r}))$, where $\boldsymbol{B}(\boldsymbol{r})$ is the magnetic field at the position $\boldsymbol{r}$ of the particle. (This is part of the *Lorentz force law*.) Note that a magnetic force cannot change the speed of a charged particle, since it always acts at right angles to the direction of motion of the particle, but it can still cause the particle to accelerate by changing the direction of the particle's motion. [*SFP*.4]

magnetic moment See *magnetic dipole*.

magnetic monopole A hypothetical 'particle' which, if it existed, would produce a purely radial magnetic field similar to the electric field of an isolated electric charge. *Maxwell's equations* imply that magnetic monopoles do not exist; so that magnetic field lines must either form closed loops (like those associated with a current-carrying wire), or they must always begin at a north pole and end at a south pole (like those associated with a *magnetic dipole*). Consequently, the *magnetic flux*, due to a magnetic field, through a closed surface is zero, since that closed surface cannot enclose any magnetic monopoles. [*SFP*.4; *DFW*.1]

magnetization The process that causes a material, subjected to an applied *magnetic field*, to produce a magnetic field of its own. [*SFP*.4]

magnification A commonly used shorthand for *linear magnification*. (See also *angular magnification*.) [*DFW*.3]

magnifying glass An optical device that, in its simplest form, consists of a single *converging* lens. In one mode of use, the magnifying glass is held close to the eye; this permits an increase in the *visual angle* subtended by an object by allowing it to be held much closer to the eye than the *normal near point* while still remaining in focus. The magnifying glass forms an enlarged *virtual image* of the otherwise too-close object at some point between the eye's *near point* (*near-point adjustment*) and *far point* (*far-point adjustment*). This device is sometimes called a simple *microscope*. [*DFW*.3]

magnifying power See *angular magnification*. [*DFW*.3]

magnitude (of a scalar) Given any *scalar* quantity, positive or negative, its magnitude is a positive quantity, equal to the value of the given scalar apart from any overall minus sign. For example, both 5 and −5 have magnitude 5. The *modulus* symbol $|\ |$ is used as an instruction to take the magnitude of the enclosed scalar. Thus, for example, $|-5| = 5$. The magnitude of a scalar is often referred to as its 'modulus' or its 'absolute value'. [*DM*.1]

magnitude (of a vector) Given any *vector* quantity $\boldsymbol{v}$, its magnitude is a positive *scalar* quantity v that indicates the 'length' or 'size' of the given vector. The *modulus* symbol $|\ |$ is sometimes used as an instruction to take the magnitude of the enclosed vector. Thus, for example, the magnitude of $\boldsymbol{v}$ may be denoted by $|\boldsymbol{v}|$ or v. If $\boldsymbol{v}$ is expressed in terms of its Cartesian components $\boldsymbol{v} = (v_x, v_y, v_z)$, then the magnitude of $\boldsymbol{v}$ is given by

$$|\boldsymbol{v}| = v = \sqrt{v_x^2 + v_y^2 + v_z^2}\ . \quad [DM.2]$$

magnitude of the acceleration due to gravity The magnitude of the downward acceleration due to gravity at the Earth's surface. Represented by the symbol g, this quantity has a value close to $9.81\ \mathrm{m\,s^{-2}}$ across much of the Earth's surface. [*DM*.1]

Magnus effect This effect whereby a spinning object, moving through a *fluid*, experiences a transverse force, perpendicular to its direction of motion and to its angular velocity. [*CPM*.4]

many worlds interpretation An interpretation of *quantum mechanics* which, in one version at least, asserts the existence of a large number of parallel universes, each of which realizes one of the possibilities encompassed by the branching wavefunction describing the state of a system and the relative state of the rest of the Universe. [*QPI*.4]

map See *linear map* and *non-linear map*.

mass energy The *energy* that a body possesses by virtue of its *mass*, as given by $E_{\mathrm{mass}} = mc^2$, where c is the speed of light in a vacuum. The existence of mass energy is one of the many implications of the *special theory of relativity*. The mass energy of a free particle is the difference between its (total) *relativistic energy* and its *relativistic translational kinetic energy*. Mass energy is also known as *rest energy*. [*PM*.3; *DFW*.4]

mass number The total number of *protons* and *neutrons* in a specified *nucleus*. The mass number is usually represented by the symbol A, and is equal to the sum of the *atomic number* Z and the *neutron number* N, so $A = Z + N$. [*CPM*.4; *QPI*.3; *QPM*.3]

mass spectrometer A device which uses *electric* and *magnetic fields* to separate particles (usually ionized atoms or molecules) of different mass (strictly charge to mass ratio) and to measure the masses of these particles. [*SFP*.4]

matter A general term for material substances, irrespective of their form.

Maxwell–Boltzmann energy distribution The equilibrium *translational energy distribution function* for *molecules* in a *gas* at (absolute) *temperature* T:

$$g(E) = \frac{2}{\sqrt{\pi}} \left(\frac{1}{kT}\right)^{3/2} \sqrt{E} \times e^{-E/kT}$$

where E denotes the *translational kinetic energy* of a molecule, i.e. $E = E_{\text{trans}} = mv^2/2$ where m and v are the mass and speed of the molecule. The product $g(E)\,\Delta E$ is the *probability* of a single molecule having translational energy between E and $E + \Delta E$. Consequently, if the total number of molecules in the gas is N, the quantity $G(E)\,\Delta E = Ng(E)\,\Delta E$ represents the total number of molecules with energy between E and $E + \Delta E$. [*CPM*.2; *QPM*.1]

Maxwell–Boltzmann speed distribution Another term for the *Maxwell speed distribution*. [*CPM*.2]

Maxwell speed distribution The equilibrium *speed distribution function* for *molecules* in a *gas* at (absolute) *temperature* T:

$$f(v) = 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} v^2 \times e^{-mv^2/2kT}$$

where m and v are the mass and speed of the molecules, and k is Boltzmann's constant. The product $f(v)\,\Delta v$ is the probability of a single molecule having translational energy between v and $v + \Delta v$. [*CPM*.2]

Maxwell's equations A set of equations assembled by James Clerk Maxwell to describe the behaviour of *electric* and *magnetic fields*. The equations can be expressed in words as follows:

1 The *electric flux*, due to an electric field, through a closed surface is proportional to the charge contained inside it. (This is related to *Coulomb's law*.)

2 The *magnetic flux* due to a magnetic field through a closed surface is zero. (This embodies the idea that *magnetic monopoles* do not exist.)

3 The magnitude of the rate of change of the magnetic flux, due to a magnetic field, through a surface is equal to the magnitude of the EMF along the boundary of the surface; the direction of the EMF opposes the change causing it. (This is essentially an expression of *Faraday's law* and *Lenz's law*.)

4 The average magnetic field along the boundary of a surface depends on the current per unit area inside the surface *and* on the rate of change of the electric field across the surface. (This recognizes current as one source of magnetic field, and introduces a changing electric field as another.)

Equations 3 and 4 embody the two key concepts of *electromagnetic induction*, namely that 'a changing magnetic field causes an electric field' and 'a changing electric field causes a magnetic field'. These two effects can be used to predict the existence of *electromagnetic radiation*, which travels at a fixed speed in a vacuum given by $c = 1/\sqrt{\varepsilon_0 \mu_0}$, where ε_0 and μ_0 are the permittivity of free space and the permeability of free space, respectively. [*DFW*.1]

mean free path The average distance that particles in a gas travel between collisions. [*QPM*.2]

mean lifetime The *time constant* τ that characterizes the *spontaneous decay* of particles that decay in a random fashion and in such a way that if there are N_0 particles in a given sample at time t then the number remaining in that sample at time $t + \tau$ will be, on average, N_0/e. The mean lifetime is sometimes referred to as the lifetime, and is related to the *half-life* $T_{1/2}$ of the particles by $T_{1/2} = \tau \log_e(2)$. [*QPM*.4]

measured average value A typical value of some quantity obtained by multiplying each possible value of the quantity by its fractional frequency and adding together all the resulting terms. [*CPM*.2]

mechanical energy The sum of *kinetic energy* and *potential energy* of a body or system. [*PM*.2]

mechanical equilibrium condition The conditions

$$\sum_i \boldsymbol{F}_i = \boldsymbol{0} \quad \text{and} \quad \sum_i \boldsymbol{\Gamma}_i = \boldsymbol{0}.$$

which ensure that a system is free from any net *external force* and any net external *torque*. Both the *linear momentum* and the *angular momentum* of such a system will be constant. [*PM*.4]

mechanics The branch of physics concerned with force and motion. [*RU*.1]

Meissner effect The effect whereby all magnetic flux is expelled from the interior of a *type I superconductor* in the transition to the superconducting state upon being cooled below the *superconducting transition temperature* T_C. The effect is due to the magnetic properties of the superconductor and is not a direct consequence of the infinite conductivity. [*QPM*.2]

meson A term used to describe any strongly interacting particle that has zero or integer *spin* (i.e. spin 0, 1, 2, etc.). Each meson is a combination of a *quark* and *antiquark*, and consequently has *baryon number* $B = 0$. Mesons are a sub-class of *hadrons*. [*QPM*.4]

metal See *metallic solid*.

metallic solid A *solid* in which the *valence electrons* are freed from their parent atoms and are bound only by the surface of the metal itself. The bonding in a metallic solid can be thought of as arising from the attraction between the lattice of positive *ions* and the *electron* gas occupying the same space. The bonding is non-directional and usually results in a close packed structure. [*QPM*.2]

metre The *SI* unit of length, represented by the symbol m. The metre is one of the seven SI *base units*, and is defined as the distance that light travels in a vacuum in 1/299 792 458 second. [*DM*.1]

Michelson–Morley experiment An experiment carried out in 1887, which used an *interferometer* in an attempt to measure the *speed* of the Earth through the *ether*. The null result effectively proved that the ether did not exist and paved the way for Einstein's *special theory of relativity*. [*DFW*.2; *DFW*.4]

microscope An optical device that, in its simplest form, uses an *objective lens* to produce an enlarged, *real image* of an object well inside the *normal near point* of the eye, this real image is viewed through an *eyepiece lens*, which forms a further enlarged *virtual image* at some point between the eye's *near point* (*near-point adjustment*) and *far point* (*far-point adjustment*). This device is sometimes called a *compound microscope*. [*DFW*.3]

microscopic A term used to indicate that the relevant size scale is very small. For example, a *system* is said to be microscopic if it is too small for its bulk characteristics to be easily measured. Microscopic systems are normally smaller than 0.1 mm across and contain fewer than 10^{17} atoms. [*CPM*.1]

microstate See *configuration*. [*CPM*.2; *CPM*.3]

microwaves *Electromagnetic radiation* with a *wavelength* between about 1×10^{-3} m and 1×10^{-1} m, or a *frequency* between about 3×10^{11} Hz and 3×10^{9} Hz. [*DFW*.2]

milli A prefix used to indicate the standard *SI submultiple* of 10^{-3}. [*DM*.1]

mirror A device for reflecting light. See *plane mirror*, *spherical mirror* and *parabolic mirror*. [*DFW*.3]

mixed bonding A kind of *bonding* that is intermediate between *ionic bonding* and *covalent bonding*. Except for the covalent bonding of identical atoms (as in the diatomic chlorine molecule Cl_2), the usual views of ionic and covalent bonding — involving either the entire transfer of *valence electrons* or the completely even sharing of a pair of valence electrons — are somewhat idealized. In practice bonding is more realistically viewed as a mixture of these types, with uneven sharing of electrons and some Coulomb attraction of ion pairs. [*QPM*.2]

model A description of a system or process that aims to capture the essence of the true situation but incorporates various simplifications or idealizations. In physics, models are often of a mathematical nature, and are frequently designed to make mathematical analysis tractable. [*DM*.1]

moderator A material used in a nuclear reactor to reduce the average speed of the fast *neutrons* released by *induced fission* reactions. The neutrons are slowed and eventually brought into *thermal equilibrium* by repeated collisions with the light nuclei of the moderator, which is usually composed of carbon in the form of graphite or hydrogen in the form of water. The resulting *thermal neutrons* can then cause further induced fission reactions thereby sustaining a chain reaction. [*QPM*.3]

modes of oscillation The different kinds of oscillation that a system can exhibit simultaneously. [*DM*.3]

modulus sign The mathematical symbol $| \; |$ used to denote the *magnitude* of the enclosed quantity. For example, $|-3.41| = 3.41$. The terms 'modulus' and 'magnitude' are often used to mean the same thing. [*DM*.3]

molar heat capacity The amount of energy required to raise the *temperature* of 1 *mole* of a specified substance by 1 K (generally under specified conditions, such as constant *pressure*, or constant volume). The *SI* unit of molar heat capacity is the J K^{-1} mol^{-1}. [*CPM*.3]

molar internal energy The *internal energy* per *mole* of a pure substance. The *SI* unit of molar internal energy is the J mol^{-1}. [*CPM*.1]

molar latent heat of melting The energy per *mole* required to melt a *solid* into a *liquid*, whilst the *temperature* remains fixed at the melting temperature. The *SI* unit of molar latent heat of melting is the J mol^{-1}. [*CPM*.1]

molar latent heat of vaporization The energy per *mole* required to vaporize a *liquid* into a *gas*, whilst the *temperature* remains fixed at the boiling temperature. The *SI* unit of molar latent heat of vaporization is the J mol^{-1}. [*CPM*.1]

molar mass The mass per *mole* of a pure substance. The *SI* unit of molar mass is the kg mol^{-1}. [*CPM*.1]

molar volume The volume per *mole* of a pure substance. The *SI* unit of molar volume is the m^3 mol^{-1}. [*CPM*.1]

mole The *SI* unit for the quantity of a pure substance, represented by the symbol mol. The mole is one of the seven SI *base units*, and is defined as the amount of substance that contains as many elementary units (atoms, molecules. ions etc.) as there are atoms in 0.012 kg of carbon-12. One mole of any pure substance therefore contains *Avogadro's number* of the basic particles (*molecules* or *atoms*) of that substance. For a pure substance made up of *atoms* (or *molecules*) of *relative atomic* (or *molecular*) *mass* M_r, one mole is a sample of mass $M_r \times 10^{-3}$ kg. [*CPM*.1]

molecular solid A solid consisting of molecules that are weakly bound together due to the action of *van der Waals forces* or because of *hydrogen bonding*. [*QPM*.2]

molecule The smallest part of a given pure substance that retains the chemical identity of that substance. From a microscopic point of view, a molecule is a particular group of *atoms* bound together in a given way. [*CPM*.1]

moment of inertia The moment of inertia about a given axis for a system of *particles*, or for a *rigid body*, is a measure of the distribution of the system's *mass* about that axis. For a system of particles with masses m_i at perpendicular distances r_i from the axis, the moment of inertia I is

$$I = \sum_i m_i r_i^2 \; .$$

A similar expression applies to a rigid body, but in that case, the continuous nature of the mass distribution means that the sum must usually be replaced by a *definite integral*. The *SI* unit of moment of inertia is the kg m^2. [*PM*.4]

momentum A *vector* quantity, useful in various situations as a measure of a body's tendency to continue in its existing state of *rotational* or *translational motion*. See *angular momentum* and *linear momentum* for further details. [*PM*.3]

monatomic A term indicating that the basic particles of a pure substance (usually a gas) are single *atoms* rather than *molecules* containing two or more atoms. [*CPM*.2]

monochromatic A term used to describe *electromagnetic radiation* of a single *frequency*. [*DFW*.2]

monopole See *magnetic monopole*. [*SFP*.4]

most probable speed The speed that is most likely for a collection of *molecules*, corresponding to the peak in the *speed distribution function*. [*CPM*.2]

multiple-scattering process A process that involves the deflection of a projectile (such as an α-particle), in a large number of individual encounters as it passes through a target (such as a foil of gold atoms). [*QPI*.1]

multiplication rule for probabilities A rule stating that; if a number of outcomes occur independently of one another, the *probability* of them all happening together is found by multiplying their individual probabilities together. [*CPM*.2]

muon A kind of *elementary particle*, similar to an *electron*, but with a mass that is about 207 times that of the electron. Muons are unstable *leptons* that spontaneously decay with a *mean lifetime* of 2.2×10^{-6} s in a *frame of reference* in which they are at rest. Some muons are naturally produced in the upper atmosphere as a result of cosmic rays from outer space interacting with atoms. Since these particular muons are travelling with respect to the Earth at a speed around 98% of the *speed of light*, their mean lifetime is extended by about a factor of five as measured in a frame of reference fixed to the Earth. This is an example of *time dilation* and an effect of *special relativity*. Muons may occur with either positive or negative charge, the positive muon (μ^+) being the *antiparticle* of the negative muon (μ^-). [*DFW*.4; *QPM*.4]

muon neutrino A kind of elementary particle that has no known substructure and is therefore regarded as a truly fundamental particle. It is the partner to the *muon* in the second *generation* of *leptons*. It has *spin* $\frac{1}{2}$, no charge and a mass of less than $0.17\,\mathrm{MeV}/c^2$. [*QPM*.4]

muon number A dimensionless quantity that is conserved in all known interactions. The *muon* has a muon number of 1, and so has the *muon neutrino*. [*QPM*.4]

mutual inductance See *coefficient of mutual inductance*. [*DFW*.1]

myopia See *short-sightedness*. [*DFW*.3]

natural frequency (a) In the context of a mechanical *oscillator*; the natural frequency is the (*angular*) *frequency* of the oscillator in the absence of any driving or damping forces. For a harmonic oscillator of mass m, subject to a linear restoring force, $F_x = -kx$, the natural (angular) frequency is $\omega_0 = \sqrt{k/m}$. [*PM*.2]

(b) In the context of an *LC circuit*; the natural frequency is the frequency of charge oscillations in the absence of resistance or driving signal. For an *LC* circuit of *inductance L* and *capacitance C*, the natural frequency is $f = 1/2\pi\sqrt{LC}$ [*DFW*.1]

natural logarithm See *logarithm to the base e*. [*PM*.2]

nearly-free electron model A *quantum-mechanical model* of the *electron gas* in *solids* that goes beyond *Pauli's quantum free-electron model* by introducing a small (spatially) periodic potential energy change, V_{pot}, to model the actual periodic crystal structure of the positive lattice ions. This additional potential energy term is included in the *Schrödinger equation* which is solved to obtain the allowed energies and wavefunctions. The allowed energies are found to be restricted to *energy bands* separated by *energy gaps*. The nearly-free electron model thus represents an approach to the *band theory of solids*. [*QPM*.2]

near point The closest point on which the eye can focus. It is conventional to assume a standard near-point distance of 250 mm for a 'normal' eye (this point is then often called the *normal near point*). [*DFW*.3]

near-point adjustment The condition in which a *magnifying glass*, *microscope* or *telescope* positions the final *virtual image* (to be observed by the eye) at the normal eye's *near point*. The *angular magnification* is slightly greater in near-point adjustment than in *far-point adjustment*, but the eye is more relaxed in the latter adjustment. [*DFW*.3]

negative (photographic) The 'reversed' image produced on photographic *film* in which bright parts of the object are rendered black (because this is where the exposed *silver halide* grains are converted into opaque silver) and dark parts of the object are rendered light. [*DFW*.3]

negative lens See *diverging lens*. [*DFW*.3]

negative mirror See *diverging mirror*. [*DFW*.3]

neutral equilibrium A type of *static equilibrium* in which a system displaced slightly from its original position has no tendency to return to that position, nor to move further away from that position. This is the kind of static equilibrium exhibited by a uniform spherical body resting on a horizontal plane. [*PM*.4]

neutrino A *spin* $\frac{1}{2}$ uncharged *lepton* of very small (possibly zero) mass. Three different types of neutrino are known; *electron neutrino*, *muon neutrino* and *tauon neutrino*. [*QPM*.4]

neutron An uncharged elementary particle with mass 1.675×10^{-27} kg (about 0.1% greater than that of the *proton*), and spin $\frac{1}{2}$. Neutrons are non-strange *baryons*, and, when free, are unstable, having a *mean lifetime* of about 15 minutes. They are found in the *nucleus* of every *atom* (except for the lightest *isotope* of hydrogen). [*CPM*.1; *QPM*.4]

neutron number The number of *neutrons* in a specified *nucleus*. The neutron number is usually represented by the symbol N and is equal to the difference between the *mass number A* and the *atomic number Z*, so $N = A - Z$. [*QPM*.3]

neutron star A highly compact stellar body composed of neutron-rich matter. Neutron stars have a typical density of order $10^{15}\,\mathrm{kg\,m^{-3}}$ (about 10^{12} times the density of water). Measured neutron star masses are typically 1.4 times the mass of the Sun, and their radii are thought to be about 8 to 10 km. Neutron stars are formed when massive stars with degenerate cores that are supported normally by electron *Pauli pressure*, collapse under their own weight. When the degenerate core of a highly evolved star acquires a mass that is greater than about $1.4M_{\text{Sun}}$, the Pauli pressure is insufficient to prevent its sudden collapse. The core undergoes extreme compression in which electrons and protons combine to yield neutrons and neutrinos. This results in an extremely violent *supernova* explosion, and leaves behind a neutron star that is prevented from further collapse by neutron Pauli pressure. [*PM*.4; *SFP*.2]

newton The *SI* unit of *force*, represented by the symbol N, and defined by the relation $1\,\mathrm{N} = 1\,\mathrm{kg\,m\,s^{-2}}$. An unbalanced *force* of magnitude 1 N will cause a

particle of mass 1 kg to accelerate at $1\,\mathrm{m\,s^{-2}}$ in the direction of the force. [*PM*.1]

Newtonian mechanics This is a branch of physics which attempts to explain the motion of objects in terms of the *forces* acting on them. It is based on *Newton's laws of motion* and incorporates other important principles, such as the laws of *conservation of energy*, *conservation of linear momentum*, and *conservation of angular momentum.* [*PM*.1]

Newtonian telescope A *reflecting telescope* that uses a *converging mirror* (the *objective* or *primary mirror*) and a small *plane mirror* (the *secondary mirror*). The secondary mirror is positioned at 45° to the *optical axis*, and directs rays coming from the primary mirror to one side of the telescope tube. An *eyepiece lens* may be positioned to view the *virtual image* directly by eye; alternatively a photographic or electronic detector may be used to capture a *real image*. (See also *telescope*.) [*DFW*.3]

Newton's first law of motion A law stating that; a body remains at rest or in a state of uniform motion unless it is acted on by an unbalanced force. Newton's first law presupposes the use of an *inertial frame of reference*. Given that such a frame is used, the law implies that a particle moving along the x-axis, that is free from any unbalanced force, will obey the uniform motion equations: $s_x = u_x t$, $v_x = u_x$ and $a_x = 0$. [*PM*.1]

Newton's law of universal gravitation See *law of universal gravitation*. [*PM*.1]

Newton's second law of motion A law stating that; an unbalanced force acting on a body of fixed mass will cause that body to accelerate in the direction of the unbalanced force, and that the magnitude of the force is equal to the product of the mass and the magnitude of the acceleration: $\boldsymbol{F} = m\boldsymbol{a}$. Newton's second law presupposes the use of an *inertial frame of reference*. Given that such a frame is used, the law implies that a particle of mass m subject to an unbalanced force with component F_x in the x-direction will obey the equation $F_x = ma_x$. For a system of particles, or an extended body, the law implies that the resultant external force is equal to the total mass times the acceleration of the *centre of mass*. Newton's second law may be expressed in terms of *momentum* as follows. The *resultant force* acting on a body is equal to the rate of change of the body's momentum: $\boldsymbol{F} = \mathrm{d}\boldsymbol{p}/\mathrm{d}t$. For a system of particles or an extended body this implies that the total external force is equal to the rate of change of the total linear momentum. [*PM*.1]

Newton's theorem A theorem stating that; the gravitational effect of any spherically symmetric body, outside its own surface, is identical to that of a single particle, with the same mass as the body, located at the centre of the body. [*PM*.1]

Newton's third law of motion A law stating that; if body A exerts a force on body B, then body B exerts a force on body A, and that these two forces are equal in magnitude but act in opposite directions. In vector notation, the law implies that $\boldsymbol{F}_{\mathrm{AB}} = -\boldsymbol{F}_{\mathrm{BA}}$, where $\boldsymbol{F}_{\mathrm{AB}}$ is the force on A due to B, and $\boldsymbol{F}_{\mathrm{BA}}$ is the force on B due to A. Such a pair of forces is sometimes called a Newton's third-law pair. [*PM*.1]

node A fixed point in space at which the disturbance (e.g. displacement of a string) due to a *standing wave* is zero at all times. (Contrast with *antinode*.) [*DFW*.2]

non-conservative force A force which is not a *conservative force*, and which, therefore, cannot be associated with a unique *potential energy* at every point. The *work* done by such a force when its point of application moves from one place to another is dependent on the path followed. *Frictional forces* are examples of non-conservative forces. [*PM*.2]

non-linear map A non-linear rule for turning one set of values into another. An example of such a non-linear rule is $y = kx(1 - x)$ (the basis of the *logistic map*) but almost any other rule would serve as an example provided it could *not* be written in the form $y = mx + c$, where m and c are constants. [*PM*.5]

non-linear system A system that is described by a *non-linear map* or a non-linear equation of motion. [*PM*.5]

non-locality The feature of *quantum mechanics* that allows it to account for the predicted and observed correlations between the results of measurements carried out simultaneously at well-separated locations. [*QPI*.4]

non-uniform motion Any form of motion in which the *velocity* is not constant. [*DM*.1]

normal The normal to any surface at a point is the line perpendicular to the surface at that point. In more general usage, normal is another word for perpendicular. [*DFW*.2]

normalization The process by which a function is scaled (i.e. multiplied by an appropriate constant) so that the resulting *normalized* function satisfies a specified *normalization rule*. For example, in the case of the time-independent wavefunction $\psi(x)$ of a particle confined to the x-axis, normalization is achieved when the area under a graph of $|\,\psi(x)\,|^2$ against x is equal to 1. [*QPI*.2]

normalization factor An overall factor (appearing in a *function*), the value of which may be chosen to ensure that the function satisfies some specified *normalization rule*. An example is the factor A in *Boltzmann's distribution law*: $p = A\mathrm{e}^{-E/kT}$. [*CPM*.2]

normalization rule A rule or condition imposed on a function or a set of related values with the aim of simplifying the interpretation of that function or those values. An example is the requirement that the sum of the *probabilities* of all the alternative outcomes of a process should equal 1. [*CPM*.2]

normalized The condition in which a specified function or a set of related values (such as the *wavefunction* of a particle, or a set of probabilities for the possible outcomes of some process) satisfies some specified *normalization rule* (such as the requirement that the probability of finding the particle somewhere should be 1).

normal near point The location of the *near point* for a 'normal' eye. It is conventionally assumed to be at a distance of 250 mm from the eyelens. [*DFW*.3]

normal reaction force The *reaction* to any *contact force*. When an object rests on (or is pressed into) a solid surface, the solid is compressed slightly. The solid resists compression by exerting a force on the object. This reactive force acts at right angles to the surface at

the point of contact, and is therefore called a normal reaction force. [*PM*.1]

no-slip condition The requirement that the *fluid* immediately next to a *solid* surface should always be stationary relative to the surface. [*CPM*.4]

n-type semiconductor A *semiconductor* that is doped with sufficient *donors* to ensure that a current can be carried by donor *electrons* in the *conduction band*. [*QPM*.2]

nuclear fission A process in which a heavy *nucleus* such as uranium splits into two smaller nuclei of similar size, usually accompanied by the emission of two or three *neutrons* and approximately 300 MeV of energy. The released energy appears mainly in the form of kinetic energy of the two fragment nuclei, with smaller amounts in the form of *γ-ray photons* and radioactive decay of the two fragments. Roughly speaking, this release of energy comes about because the process involves a transition from a region of low B/A to a region of higher B/A in the *binding energy per nucleon* curve. The energy released in fission reactions is the source of the energy released in atomic bombs and nuclear power stations. [*QPM*.3]

nuclear fusion A processes in which two nuclei 'fuse' together to form a heavier *nucleus*. If the nucleus produced has *mass number* $A \leq 56$ (e.g. ^{56}Fe) or thereabouts, the process is likely to be exothermic, i.e. it will release energy. Fusion is crucial in stars for both energy release and for the production of the lighter elements, from helium up to iron (Fe), from primordial hydrogen. Fusion reactions are also the basis for the energy released in hydrogen bombs. [*QPM*.3]

nuclear shell model A model of the *nucleus* based on the observation that many nuclear properties vary with *atomic number* and *neutron number* in a slow and regular fashion suggesting the existence of energy shells for nucleons analogous to the electron shells in *atoms*. (See also *magic numbers*.) Shell effects in nuclei are not as strong as in atoms. [*QPM*.3]

nucleon A term used to mean either a *proton* or a *neutron*. [*QPM*.3]

nucleus The positively charged core of an *atom*, which accounts for nearly all of its mass. A nucleus consists of one or more *protons* and a number of *neutrons*. (See also *atomic number*, *mass number*, and *neutron number*.) [*CPM*.1; *QPI*.1; *QPM*.4]

number density The number of particles per unit volume, usually represented by the symbol n. The *SI* unit of number density is m^{-3}. [*CPM*.1]

object distance A signed quantity, usually represented by the symbol u, the magnitude of which is equal to the distance from a *lens* or *mirror* to an object whose *image* is being produced by that lens or mirror. According to the *real-is-positive convention*, the object distance is positive for *real objects* and negative for *virtual objects*.

objective See *objective lens* and *objective mirror*. [*DFW*.3]

objective lens The *lens* in a *microscope* or *refracting telescope* that receives the incident radiation from the object. Often just called the *objective*. The objective lens of a telescope is sometimes simply referred to as the objective. [*DFW*.3]

objective mirror The *mirror* in a *reflecting telescope* that receives the incident radiation from the object. Often simply called the *objective*. [*DFW*.3]

observable A physical property of a system that might be measured in a suitable experiment. Examples include *position*, *momentum* and *energy*. [*QPI*.4]

observer A fictional individual dedicated to the use of a specific *frame of reference* to measure quantities such as position, time, speed, velocity and acceleration. An observer is usually thought of as being at rest in his or her frame of reference, but is not necessarily at the origin, or any other particular position. The observer associated with a specified frame of reference is essentially an experimenter dedicated to the use of that frame. [*PM*.1; *DFW*.4]

occupation factor The average number of particles occupying a given quantum state in *thermal equilibrium*. The occupation factor for distinguishable particles is the *Boltzmann occupation factor*. For *indistinguishable bosons* it is the *Bose occupation factor*, and for indistinguishable fermions it is the *Fermi occupation factors*. [*QPM*.1]

odd function A function $f(y)$ that satisfies the condition $f(y) = -f(-y)$, for all values of y. [*DM*.3]

ohm The *SI* unit of *resistance*, represented by the symbol Ω, and defined by the relation $1\,\Omega = 1\,\text{V}\,\text{A}^{-1}$. [*SFP*.3]

Ohm's law An empirical law, applying only to certain materials and only under certain circumstances, stating that; the *potential difference* V across a sample is directly proportional to the *current* i that flows through it. The proportionality is usually expressed as $V = iR$, where V drops in the direction of the current flow, and the constant of proportionality R represents the *resistance* of the sample. As long as Ohm's law is applicable, the resistance of a sample will be independent of potential difference and current. [*SFP*.3]

omega minus A *spin* $\frac{3}{2}$ *baryon* (represented by the symbol Ω^-) the prediction of which was one of the early successes of the *quark* model. [*QPM*.4]

ontological interpretation See *Bohm's theory*. [*QPI*.4]

operationalism A philosophical doctrine asserting that only observationally defined quantities should be allowed to enter at any stage into a theory. [*QPI*.4]

operator A mathematical entity (such as the *derivative* operator, d/dt) that acts on a *function* and thereby changes it into another function. In the case of the derivative operator, the function upon which it acts is transformed into the derivative of the function. [*DM*.1]

optical axis The axis about which a *lens* or *mirror* is rotationally symmetrical. If the lens does not have circular symmetry (as with a *cylindrical lens*), the optical axis can alternatively be defined as the axis passing through the *optical centre* of the lens that is perpendicular to the 'plane' of the lens. [*DFW*.3]

optical centre (of a lens) The axial point at the centre of a *thin lens* through which rays will pass without being deviated. [*DFW*.3]

optical fibre A glass fibre used to transmit light signals that can carry coded binary information. The

principle of operation of optical fibres relies on *total internal reflection*. [*DFW*.2]

optic nerve A mass of connected nerve fibres which links the *retina* of the eye to the brain. [*DFW*.3]

orbital angular momentum quantum number A *quantum number*, conventionally represented by the symbol *l*, that characterizes the magnitude *L* of the *orbital angular momentum* of an electron in an atom:

$$L = \sqrt{l(l+1)}\,\hbar.$$

The quantum number *l* can take integer values from 0 to $n - 1$, where *n* is the *principal quantum number*. [*QPI*.3]

orbital magnetic quantum number A *quantum number*, conventionally represented by the symbol m_l, that determines the *z*-component, L_z, of the *orbital angular momentum* of an electron in an atom:

$$L_z = m_l\hbar.$$

The quantum number m_l can take the values $m_l = 0, \pm 1, \pm 2, \ldots, \pm l$, where *l* is the *orbital angular momentum quantum number*. [*QPI*.3]

ordered pair A pair of quantities, usually presented in the form (x, y), and subject to an interpretation that depends on their order, so that (x, y) has a different meaning from (y, x) as long as $y \neq x$. [*DM*.2]

order of diffraction A whole number *n*, associated with each of the intensity maxima seen in a diffraction pattern. When a beam of light passes through a double slit or a *diffraction grating*, the beam transmitted in the same direction as the incident beam is said to be the 'zeroth order' diffracted beam ($n = 0$). The next peaks on either side are called 'first-order peaks' and are associated with $n = 1$ or 'first-order' diffracted beams, the next are 'second-order' ($n = 2$), and so on. The order of diffraction appears in the *diffraction equation*:

$$n\lambda = d\sin\theta_n$$ [*DFW*.2]

origin An arbitrarily chosen reference point from which *coordinates* are measured in a *coordinate system*. In one dimension, the origin is the point at which the *position coordinate* is zero. [*DM*.1]

oscillation A continuous back and forth (or up and down) motion that can be characterized by an *amplitude* and a *period*. [*DM*.3]

pairing energy The increase in *binding energy per nucleon* for nuclei that have even numbers of *protons* and/or *neutrons*, rather than odd numbers. [*QPM*.3]

parabola A curve which may be described by an equation of the form $y = ax^2 + bx + c$ where *a*, *b* and *c* are constants, and *a* is non-zero. The parabola belongs to the family of curves known as *conic sections*, and is produced by the intersection of a cone and a plane inclined parallel to one of the sloping sides of the cone. [*DM*.2]

parabolic mirror A mirror whose surface has a parabolic shape and so does not suffer from *spherical aberration*. Contrast with *spherical mirror* and *plane mirror*. [*DFW*.3]

parallel plate capacitor A *capacitor* consisting of two parallel conducting plates of area *A*, a distance *d* apart and separated by an insulating material of *relative permittivity* ε_r. Its *capacitance* is given by: $C = \varepsilon_r\varepsilon_0 A/d$, where ε_0 is the *permittivity of free space*. [*SFP*.2]

paramagnetic A term used to describe materials which, when placed in a *magnetic field*, become magnetized in the direction parallel to the applied field. The total magnetic field within the material is therefore greater than the applied magnetic field that causes the *magnetization*. (Contrast with *diamagnetic*.) [*SFP*.4]

parameter A quantity that is constant in a particular case but may vary from one case to another. [*DM*.3; *PM*.5]

parent nucleus A term used to describe the initial *nucleus* in any nuclear decay process. The final nucleus that results from the decay is known as the *daughter nucleus*. [*QPM*.3]

particle (a) In the context of *classical physics*; a particle is an object that has no spatial extent and can therefore be thought of as existing at a single point in space. It has no size, shape or internal motion though it may have intrinsic properties such as mass and charge, as well as position, velocity and acceleration. Although the concept of a classical particle is an idealization, the *centre of mass* of an extended body moves just like a particle with the same mass as the body, subject to the combined effect of the *external forces* acting on the object. [*DM*.1; *PM*.1]

(b) In the context of *particle physics*; a particle (also known as an 'elementary particle' in this context) is a piece of matter that is of sub-nuclear size. Such particles include protons and neutrons, as well as electrons and quarks, and may or may not be truly fundamental constituents of matter.

particle accelerator A device in which charged (elementary) particles are accelerated to high energies. There are two distinct types, known as *linear accelerators* and *cyclic accelerators*. [*PM*.3; *QPM*.4]

particle physics The branch of physics that concerns the fundamental constituents of matter, and the manner in which those constituents interact. In practice, particle physics uses the methods of *quantum physics* to study all structures of sub-nuclear size, including *protons* and *neutrons* (which are known to contain *quarks*) and *electrons* (which have no known internal structure). The 'real' particles that are the concern of particle physics are sometimes referred to as 'elementary particles', in order to distinguish them from the 'ideal' particles of *classical physics*.

pascal The *SI* unit of *pressure*, represented by the symbol Pa, and defined by the relation $1\,\text{Pa} = 1\,\text{N}\,\text{m}^{-2}$. [*PM*.1; *CPM*.1]

path difference The difference in length of two specified routes. If the two routes join different points in a *coherent source* to the same point in an *image*, then *constructive* or *destructive interference* can take place between *waves* following those routes. [*DFW*.2]

path of stability A graphical feature seen when the *lifetime* of each known *nucleus* is indicated on a *Z–N plane* (a plot of *atomic number Z* against *neutron number N*). The points corresponding to stable and very long-lived nuclei, i.e. those naturally abundant on Earth, all lie close to a narrow curving path — the path of stability. [*QPM*.3]

Pauli pressure The *pressure* exerted by a *gas* of *fermions* as a direct consequence of *Pauli's exclusion principle*. When a system of fermions (such as *electrons* or *neutrons*) is at a relatively low temperature, the energy levels of the system fill from the ground state upwards. Because of the exclusion principle many particles are forced into quite high energy levels, in spite of the relatively low thermal energy. These particles have a high average translational energy and, by the usual kinetic theory argument, give rise to a large pressure. It is this that constitutes the Pauli pressure. The electrons in a *white dwarf* star provide an example of this phenomenon: the star is supported against gravitational collapse by the Pauli pressure exerted by its electrons. [*SFP*.2]

Pauli's distribution The energy *distribution function*, $G_e(E)$, for *free electrons* in a *metal* at (absolute) *temperature T*. According to *Pauli's quantum free-electron model*, the function $G_e(E)$ is the product of the *density of states function for electrons* and the *Fermi occupation factor*: $G_e(E) = D_e(E)F_F(E)$. The quantity $G_e(E)\,\Delta E$ represents the number of free electrons in the metal with energy between E and $E + \Delta E$. [*QPM*.1]

Pauli's exclusion principle A principle asserting that; no two *electrons* can occupy the same *quantum state*. Thus, for example, if two electrons in a particular atom have the same values of the quantum numbers n, l and m_l, they must also have opposite *spins*, i.e. $m_s = +\frac{1}{2}$ for one, while for the other $m_s = -\frac{1}{2}$. [*QPI*.3; *QPM*.3]

Pauli's quantum free-electron model A model of conductivity in metallic solids, formulated by Wolfgang Pauli, in which the *free-electron* gas in a metal is treated as a *quantum gas* of *fermions*. [*QPM*.1]

penetration depth The thickness of the surface layer of a superconductor within which the magnetic flux exclusion observed in the *Meissner effect* is incomplete. It is a persistent supercurrent flowing in this layer that creates the cancellation of the applied magnetic field. [*QPM*.2]

performance (of a refrigerator) The ratio of the net amount of *heat* absorbed by the circulating *fluid* to the net amount of *work* done on that fluid. [*CPM*.3]

period The minimum time needed for a repetitive action to recur. If the action can be described by a *periodic function* $f(t)$, then the period T is the smallest value such that $f(t + T) = f(t)$ for all t. An example is the time T for a simple harmonic oscillator (described by $x = A\sin(\omega t + \phi)$) to complete one full cycle. Other examples include the period of an elliptical orbit, the period of rotation of a spinning body, and (in the context of waves) the time interval between one part of a wave passing a fixed point and the next identical part of the wave passing the same fixed point. [*DM*.3; *DFW*.2]

period doubling The phenomenon whereby the period of the *limit cycle* of a system undergoes a sequence of doublings as the system approaches a state of *chaos*. [*PM*.5]

periodic function A function, $f(t)$ say, with the property that, for all values of t, $f(t + T) = f(t)$ for some particular value of T. The smallest value of T that satisfies this requirement is said to be the *period* of the function. For example, the periodic functions $\sin(\theta)$ and $\cos(\theta)$ are each periodic with period 2π. [*DM*.3]

periodic motion Repetitive motion characterized by the requirement that $\boldsymbol{r}(t + T) = \boldsymbol{r}(t)$ for some fixed value of T and all values of t. [*DM*.3]

periodic time See *period*. [*DM*.3]

periods The horizontal rows in the *Periodic Table* of the elements. Elements in a given period all have the same *principal quantum number n* in the outer *shell* and the *subshells* are filled up as one progresses from the left to the right across the period. [*QPI*.3]

permeability of free space The physical constant $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}} = 4\pi \times 10^{-7}\,\mathrm{kg\,m\,C^{-2}}$, that plays a role in determining the magnitude of *magnetic force* between two current-carrying wires separated by a vacuum. [*SFP*.4]

permittivity of free space The physical constant $\varepsilon_0 = 8.854 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$, that plays a role in determining the magnitude of the *electrostatic force* between charged particles separated by a vacuum. [*SFP*.1]

phase A measure of the stage in its cycle that an *oscillator* has reached at a specified time, or the stage that a *wave* has reached at a specified time and position. In the case of a *simple harmonic oscillator* described by $x(t) = A\sin(\omega t + \phi)$, the phase is $\omega t + \phi$, where ω is the *angular frequency* and ϕ is the *phase constant* or *initial phase*. Similarly, in the case of a *travelling wave* represented by the equation $y(x, t) = A\sin(kx - \omega t + \phi)$, the phase is $(kx - \omega t + \phi)$, where k is the *angular wavenumber*. Two waves are said to be 'in phase' if their phases are equal at a particular point in space and instant of time; they are said to be 'out of phase' if their phases differ by exactly π radians at that point and instant. [*DM*.3; *DFW*.2]

phase cell An entity that corresponds to specified ranges of position and velocity and which may, therefore. be used to describe the position and velocity of a particle to within a given precision. [*CPM*.2]

phase constant The constant part of the *phase* of an *oscillation* or a *wave*, usually represented by the symbol ϕ. The phase constant is sometimes called the 'initial phase', since it determines the phase of the oscillation (or wave) at $t = 0$ (and $x = 0$). [*DM*.3; *DFW*.2]

phase difference The difference between the *phase* of two or more *waves* or *oscillations*, under specified conditions. Two or more waves are said to be 'in phase' at a particular point if their phase difference at that point is always zero. Two oscillations with the same frequency, such as

$$x_1 = A\sin(\omega t + \phi_1) \quad \text{and} \quad x_2 = A\sin(\omega t + \phi_2)$$

are said to be 'in phase' if their phase difference $\phi_2 - \phi_1$ is zero. [*DM*.3; *DFW*.2]

photoelectric effect The effect whereby *electrons* are emitted from matter (usually from a metallic electrode) when *electromagnetic radiation* of sufficiently high *frequency* is incident on it. [*QPI*.1]

photographic emulsion A special type of photographic film in which charged particles leave tracks. An important means of detecting particles in high-altitude *cosmic ray* experiments. [*QPM*.4]

photon A particle of *electromagnetic radiation*. More properly, a *quantum* of the *electromagnetic field*. For *monochromatic* radiation of *frequency* f the quantum of energy is, according to *Planck's law*, $E = hf$ where h is *Planck's constant*. Each photon of that radiation will carry just one quantum of energy and will also carry *momentum* $\boldsymbol{p}$ of magnitude $p = h/\lambda$, where λ is the *wavelength* of the radiation. The notion that electromagnetic radiation might be treated as a collection of particles was, to some extent, prefigured by Einstein's explanation of the *photoelectric effect* in 1905. More direct support was provided in 1923 by the *Compton effect*, but the term 'photon' was not actually introduced until 1926, by G. N. Lewis. Viewed as an e*lementary particle*, the photon is the *exchange particle* for the *electromagnetic interaction*. It has *spin* 1, no charge, zero mass, and is stable. It is often represented by the symbol γ. [*RU*.1; *QPI*.1, *QPM*.4]

pion A kind of *elementary particle*. A *spin* 0 *meson* with mass of about 140 MeV/c^2 (about one-quarter of a proton's mass). There are three kinds of pion, denoted π^+, π^-, π^0 according to charge. [*QPM*.4]

pivot A short shaft or axle about which a body, such as a *lever*, can rotate. [*PM*.4]

Planck–Einstein formula The formula

$$E = hf$$

that relates the *energy E* of a *photon* of *monochromatic electromagnetic radiation* to the *frequency* f of that radiation where $h = 6.626 \times 10^{-34}$ J s. is *Planck's constant*. [*QPI*.1]

Planck's constant The constant h (= 6.626×10^{-34} J s) introduced by Max Planck to explain the radiation emitted by blackbodies. It also appears in Einstein's theory of the *photoelectric effect* and in the *Planck–Einstein formula*. In fact, it appears in practically every equation of *quantum mechanics* but never in those of classical physics. [*RU*.1; *QPI*.1]

Planck's law See *Planck–Einstein formula*. [*QPI*.1]

Planck's radiation law A law stating that; the *energy distribution function* for *photons* in *blackbody radiation* at (absolute) *temperature* T, is given by $G_p(E) = D_p(E)F_B(E)$ where $D_p(E)$ is the *density of states function for photons* and $F_B(E)$ is the *Bose occupation factor*. The quantity $G_p(E)\,\Delta E$ represents the number of photons in the radiation with energy between E and $E + \Delta E$. [*QPI*.1; *QPM*.1]

plane mirror A mirror with a flat, plane surface (no curvature). Such a mirror will reflect light (and produce same-size images) but has no focusing properties. Contrast with *spherical mirror* and *parabolic mirror*. [*DFW*.3]

plane polar coordinate system A *coordinate system* in which the position of a point in a plane is specified by the *ordered pair* (r, θ) where r is the distance of the point from a selected *origin* and θ is the angular displacement, measured at the origin, of the point from a specified reference line that passes through the origin. [*DM*.3]

plane polarized A term used to describe a *transverse wave* in which the transverse vibrations occurring at all points on the path of the wave are all in the same plane. In such cases the plane defined by the direction of the vibrations and the direction of propagation of the wave is called the plane of polarization of the wave. [*DFW*.2]

plane wave A *wave* in which the *wavefronts* form parallel lines (in two dimensions) or parallel planes (in three dimensions). At any given time, the *phase* of such a wave will have the same value at all points on a plane that is perpendicular to the *direction of propagation* of the wave. [*DFW*.2]

plane wavefront A plane on which the *phase* of a *wave* has the same value at all points. The existence of such planes is a characteristic of a *plane wave*. [*DFW*.2]

plasma A highly ionized gas, that is electrically neutral overall but consists almost entirely of charged particles (*electrons* and positive *ions*). Plasma is sometimes described as the fourth phase of matter. On the Earth's surface it is only found in small-scale devices, such as discharge tubes and nuclear reactors. However, on the large scale, plasma is the commonest form of visible matter in the Universe; stars and interstellar space contain large amounts of matter in the plasma state. [*CPM*.1 *SFP*.3]

plum-pudding model of the atom An atomic model, due to J. J. Thomson in which electrons are contained (like plums in a pudding) in a sphere of positively charged material of about 10^{-10} m radius. [*QPI*.1]

p–n junction A region (usually a thin layer) within a semiconductor where the *doping* changes from *p-type* to *n-type*. A p–n junction is usually associated with a (similarly narrow) *depletion region* in which mobile charge carriers are relatively rare due to the recombination of *electrons* and *holes*. A p–n junction can act as a *rectifier*, passing a large current from the p-region to the n-region, but very little current in the reverse direction. Such junctions are found in nearly all semiconductor devices such as *transistors* and *light-emitting-diodes*. [*QPM*.2]

point charge A charged particle (usually in a context where the mass of the particle is irrelevant). Although the concept of a point charge is an idealization, charged bodies whose sizes are negligible compared with the distances between them may be modelled as charged particles. [*SFP*.1]

point object (or source) An idealized object (or source of light) in an optical system; it has no appreciable spatial extent and thus gives rise to *spherical wavefronts*. A point object subtends a *visual angle* of zero. [*DFW*.3]

Poiseuille flow The kind of steady flow exhibited by an *ideal fluid* passing through a pipe. [*CPM.4*]

polar coordinate system See *plane polar coordinate system* and *spherical polar coordinate system*.

polarization The property of a *transverse wave* that implies the existence of a restriction on the direction of the transverse vibrations. (See *plane polarized* for an example of such a restriction.) [*DFW*.2]

polycrystalline solid A solid consisting of many tiny crystals joined at their boundaries. The formation of such a solid is the result of the growth and merger of many randomly oriented crystals that originate more-or-less simultaneously at different locations. [*QPM*.2]

polynomial A *function* that may be written in the form $f(x) = A + Bx + Cx^2 + Dx^3 + \ldots$,where A, B, C, etc. are constants. Special cases of polynomial functions include constants, *linear functions*, *quadratic functions* and *cubic functions*. [*DM*.1]

population inversion The phenomenon occurring in a material medium that is required for *laser* action on a suitable optical transition between two *energy levels* of the atoms of that medium. Population inversion implies the maintenance of a higher population of atoms in the upper level of the transition than the lower, so that incident resonant radiation will, on average, stimulate emission and be amplified rather than being absorbed. [*QPI*.3]

position (vector) The quantity that determines the location of a point relative to the origin of a specified *coordinate system.*

In one dimension the position of a point can be specified by means of a single coordinate value, x say. The motion of a particle that moves along the x-axis can then be described by expressing its *x-coordinate* (its instantaneous position) as a function of time.

Position is a vector quantity characterized by a *direction* as well as a *magnitude*. In one dimension the sign of a single coordinate value (such as x) suffices to determine the direction relative to the origin, but in two or three dimensions more information is required. This is often provided by expressing the position vector of a point in terms of its Cartesian components. Thus, a point with position coordinates (x, y, z), has the position vector $\boldsymbol{r} = (x, y, z)$. The magnitude of this position vector is the distance between the origin and the specified point, and is given by

$$r = |\boldsymbol{r}| = \sqrt{x^2 + y^2 + z^2}. \quad [DM.1; DM.2]$$

position coordinate See *coordinate*. [*DM*.1]

position–time graph A *graph* showing how the position (usually in one dimension) of a particle depends on time. It is conventional to plot the position on the vertical axis and the time on the horizontal axis. The *gradient* of the position–time graph at any particular time is equal to the *velocity* of the particle at that time. [*DM*.1]

positive lens See *converging lens*. [*DFW*.3]

positive mirror See *converging mirror*. [*DFW*.3]

positivism A philosophical doctrine asserting, in its most extreme form, that no sentence is meaningful unless it can be directly verified by means of the senses. This view was fashionable at the time when *quantum mechanics* was first being developed and had some influence on the *Copenhagen interpretation*. [*QPI*.4]

positron The *antiparticle* to the *electron*. It is represented by the symbol e^+. [*QPM*.4]

positron emission tomography A medical imaging technique involving the annihilation of *electrons* and *positrons*. Tomography is a technique for imaging a chosen two-dimensional section, or slice, of an internal organ or tumour, etc., using penetrating radiations, traditionally beams of X-rays. In positron emission tomography, or PET, the penetrating radiation comes from the annihilation of positrons released by a β^+-emitting isotope introduced deliberately into the region to be imaged. [*QPM*.3]

potential See *electric potential* or *gravitational potential* as appropriate.

potential difference The difference in *potential* between two specified points. In electrostatics, potential difference is usually given the symbol ΔV. However, when discussing *capacitors* and electric circuits, the symbol V is conventionally used. [*SFP*.2]

potential energy The *energy* that a body possesses by virtue of position, shape or internal structure. Typical examples are *gravitational potential energy*, *strain potential energy* and *electrostatic potential energy*. A potential energy may be associated with each *conservative force* that acts on a body or between a system of bodies. The potential energy, E_{pot}, associated with any particular configuration of a system is the *work* that would be done by the relevant conservative force in going from that configuration to an agreed reference configuration that has been arbitrarily assigned zero potential energy. Because of the arbitrary nature of this reference configuration, only changes in potential energy are physically significant. The change in potential energy, when a system goes from some initial configuration to some final configuration, is minus the work done by the relevant conservative force during that change. (Note that this is *not* generally equal to the work done by any external forces that bring about the change, since those forces may be non-conservative.)

$$E_{pot}(\text{final}) - E_{pot}(\text{initial}) = \Delta E_{pot} = -W_{cons}(\text{initial} \rightarrow \text{final})$$

(See also *gravitational potential energy* and *strain potential energy*.) [*RU*.1; *PM*.2]

potential well A region of space in which the *potential energy* of a *particle* is lower than in the surrounding region. In *classical physics*, a particle within the well that has less energy in total than the potential energy it would have in any region immediately adjacent to the well, will be *bound* and will remain permanently confined within the well. In *quantum physics*, such a particle may be able to escape from the well, thanks to the phenomenon of *tunnelling*. [*QPI*.2]

power (a) In the context of *mechanics*, power is the property of a system that measures the rate at which *work* is done and *energy* transferred. (Care must be taken to specify whether the energy is transferred to or from the system.) The *SI* unit of power is the *watt* (W), where $1\,\mathrm{W} = 1\,\mathrm{J\,s^{-1}}$. The instantaneous power delivered by a force $\boldsymbol{F}$ acting on a body moving with velocity $\boldsymbol{v}$ is given by

$$P = \frac{\mathrm{d}W}{\mathrm{d}t} = \boldsymbol{F} \cdot \boldsymbol{v}. \quad [PM.2]$$

(b) In the context of *optics*, the power of a lens is a measure of the 'ray-bending' ability of the lens. It is defined as the reciprocal of the lens's *focal length* (i.e. $P = 1/f$). If f is expressed in metres, then P will be measured in *dioptres*. According to the *real-is-positive convention,* a *diverging lens* will have a negative focal length and hence a negative power; a *converging lens* will have a positive power. [*DFW*.3]

pp chain See *proton–proton chain*. [*QPM*.3]

precession A form of motion, exhibited by *gyroscopes*, spinning tops and other such rotating bodies, in which a body's *angular momentum* vector swings around a fixed direction in space, describing a cone. [*PM*.4]

predicted average value The typical value of some quantity as predicted by multiplying each possible value of the quantity by its *probability* and then adding together the results. [*CPM*.2]

presbyopia A defect of vision, common in older age, caused by the eye muscles weakening and the eyelens tissues stiffening. The most noticeable effect is to cause loss of close vision (though in practice the whole range of *accommodation* is reduced), thus requiring the prescription of reading glasses or *bifocal spectacles*. Compare with *long-sightedness* and *short-sightedness*. [*DFW*.3]

pressure A macroscopic property of a system (such as a fluid), defined as the magnitude of the perpendicular *force* per unit area exerted by the system on a planar surface. In the case of a *fluid*, the pressure can be determined at any point by introducing pressure detectors that move with the fluid. The *SI* unit of pressure is the *pascal* (Pa), where $1\ \mathrm{Pa} = 1\ \mathrm{N\,m^{-2}}$. [*PM*.1; *CPM*.1; *CPM*.4]

pressure gradient The rate of change of *pressure* with respect to position in a given direction (e.g. $\mathrm{d}P/\mathrm{d}z$). [*CPM*.4]

primary cosmic rays Particles, mainly *protons*, arriving at the top of the Earth's atmosphere and coming directly from space. Such particles have a range of energies, but the most energetic protons can have energies in excess of 10^{18} eV. [*QPM*.4]

primary mirror Another name for the *objective mirror* in a *reflecting telescope*. [*DFW*.3]

prime focus An alternative name for the *focal point*, particularly of an *objective mirror* in a *reflecting telescope*. It is the first point to which parallel rays converge before (possibly) encountering other lenses or mirrors. [*DFW*.3]

principal focus An alternative name for the *focal point* of a *lens* or *mirror*. (See also *prime focus*.) [*DFW*.3]

principal quantum number A *quantum number*, conventionally represented by the symbol n, that is used (along with other quantum numbers) to label the *quantum state* of an electron in an atom. It plays a similar role to the Bohr quantum number (also denoted n) in that it is chiefly responsible for determining the energy of an electron in an atom (though in heavy atoms the energy also depends on the *orbital angular momentum quantum number, l*). The quantum number, n, can take any integer value from 1 upwards. [*QPI*.3]

principle of complementarity A principle of *quantum mechanics*, introduced by Niels Bohr, asserting that it is acceptable to use classically incompatible forms of language (such as those concerning waves and particles) when discussing quantum phenomena, though not simultaneously. Complementarity implies that the properties displayed by a *quantum system* depend on the apparatus used to examine it, and the properties associated with a system cannot be spoken of in isolation from the means used to determine them. [*QPI*.4]

principle of conservation of angular momentum See *conservation of angular momentum*. [*PM*.4]

principle of conservation of energy See *conservation of energy*. [*PM*.2]

principle of conservation of linear momentum See *conservation of linear momentum*. [*PM*.3]

principle of conservation of mechanical energy See *conservation of mechanical energy*. [*PM*.2]

principle of dynamic similarity A principle asserting that; two *fluid* flows referring to geometrically similar situations, with the same *Reynolds number*, are similar when each is described in terms of the appropriate scaled variables. [*CPM*.4]

principle of energy conservation A principle asserting that; the total energy of the *Universe* (i.e. a *system* and its *environment*) is constant. [*CPM*.3]

principle of entropy increase A principle asserting that; there exists a function of state, known as *entropy*, which increases during any naturally occurring change of an *isolated macroscopic system*. [*CPM*.3]

principle of relativity A principle asserting that; the laws of physics can be written in the same form in all *inertial frames* of reference. As originally put forward by Galileo, the principle of relativity covered only the laws of *mechanics*. The realization that its reach extended to the laws of *electromagnetism*, was the insight that led Einstein to the development of his *special theory of relativity*. [*RU*.1; *DFW*.4]

principle of superposition (a) In the context of *waves*, the principle of superposition asserts that; if two or more waves meet at a point in space, then at each instant of time the net disturbance at that point is given by the sum of the disturbances created by each of the waves individually. [*DFW*.2]

(b) In more general contexts the principle of superposition asserts that; for certain equations, the *linear superposition* of any number of solutions to the equation is also a solution to the equation. The equations (including differential equations) to which this principle applies must have a mathematical property known as linearity. The *time-dependent Schrödinger equation* of *quantum mechanics* is one of these equations, as is the wave equation of *classical physics*. Hence the applicability of the principle to waves and *time-dependent wavefunctions*. [*QPI*.4]

probability A numerical measure of relative likelihood of the possible outcomes of a process. It is conventional to use a probability of 1 as an indication of certainty. According to this convention, the probability of any particular outcome will be a number between 0 (impossibility) and 1 (inevitability), and will be the fraction of times that outcome is expected to happen in the long run. [*RU*.1; *CPM*.2]

probability density The probability per unit volume (in three dimensions) of detecting a particle in the vicinity of a given point. If the *wavefunction* describing the particle is *normalized*, the probability density is equal to $|\Psi|^2$, the square of the magnitude of the wavefunction. For an electron in an atom, described by the time-independent wavefunction

$$\psi(r, \theta, \phi) = \psi_1(r) \times \psi_2(\theta) \times \psi_3(\phi)$$

the probability density for detection at the point with *spherical polar coordinates* (r, θ, ϕ) is

$$|\psi(r, \theta, \phi)|^2 = |\psi_1(r)|^2 \times |\psi_2(\theta)|^2 \times |\psi_3(\phi)|^2.$$

The *SI* unit of (three-dimensional) probability density is m^{-3}. For a particle confined to one dimension, the probability density is defined as the probability per unit length of detecting the particle in the vicinity of a given point, and the SI unit of (one-dimensional) probability density is m^{-1}. [*QPI*.3]

probability wave A *wave* (also known as a de Broglie wave) that is associated with a particle in *quantum physics*. The wavelength of the wave is related to the particle's momentum magnitude p by means of the *de Broglie formula* ($\lambda_{dB} = h/p$), while the square of the wave's amplitude at any given point is proportional to the probability of detecting the particle in the vicinity of that point. The concept of a probability wave is a crude precursor to the more precise notion of a *time-dependent wavefunction*. [*QPI*.2]

process The sequence of changes taking place in a *system* as it makes a transition from one *state* to another. [*CPM*.3]

projectile A term used to refer to any object launched into unpowered flight near the Earth's surface so that it is subject only to *air resistance* and the effect of *terrestrial gravity*. If a projectile is modelled as a *particle*, and the effect of air resistance is ignored, then the *trajectory* of the projectile will be a *parabola*. [*DM*.2]

proportionality A term used to describe a relationship between two quantities, y and x say, in which altering one of the quantities by a certain factor implies altering the other by the same factor. The existence of such a relationship is indicated by saying that y is proportional to x or by writing $y \propto x$. The proportionality of x and y implies that they are related by an equation of the form

$$y = kx$$

where k is a constant, known as the *constant of proportionality*.

proton A kind of *elementary particle* found in the *nucleus* of every *atom*. Protons carry a positive charge $+e$ ($= 1.602 \times 10^{-19}$ C) and have a mass of 1.673×10^{-27} kg ($= 938.3\,\mathrm{MeV}/c^2$). The mass of a proton is about 0.1% less than the mass of a *neutron* and the two particles have similar sizes (about 10^{-15} m). The proton is a stable *baryon* of *spin* $\frac{1}{2}$. [*CPM*.1; *QPI*.1; *QPM*.4]

proton–proton chain A chain of nuclear reactions, the net effect of which is that hydrogen nuclei (*protons*) undergo *nuclear fusion* to become helium nuclei with the release of energy. This cycle occurs in the central region of the Sun and is the main source of the Sun's energy. [*QPM*.3]

psi particle A kind of *elementary particle*. A relatively long-lived *meson* (represented by the symbol ψ) consisting of a *charm* and an anticharm *quark* ($c\bar{c}$). The discovery of the psi particle (as a very narrow *resonance*) provided the first direct evidence of the existence of the charm quark. [*QPM*.4]

p-type semiconductor A *semiconductor* that is doped with sufficient *acceptors* to ensure that a current can be carried by *holes* in the *valence band*. [*QPM*.2]

pulsar An astronomical source of short pulses of radio emission at highly regular intervals, typically in the range 1 ms to about 3 s. There is very strong evidence that pulsars are highly magnetized, rapidly rotating *neutron stars*. The observed pulsing is explained by supposing that the neutron star somehow produces a continuous beam of radio emission that sweeps across the observers location (like the beam from a lighthouse) as a result of its source's rotation. [*PM*.4; *SFP*.2]

pumping The mechanism by which a *population inversion* is maintained on a laser transition in an appropriate medium. There are many different ways to achieve this, such as electrical discharges, irradiation with light, possibly combined with collisional transfer of population to the upper laser level. [*QPI*.3]

pupil The (apparently black) hole at the centre of the eye's *iris* through which light is admitted to the eye. In a typical human eye, the pupil diameter can be varied from about 2 mm (in bright light conditions) to about 8 mm (when the eye is *dark adapted*). [*DFW*.3]

***PVT* surface for any ideal gas** A surface representing the sets of values of *pressure P*, volume V and *temperature T* that characterize the *equilibrium states* of a given *macroscopic system* (such as a sample of matter). The surface is a pictorial representation of the system's *equation of state*. [*CPM*.1; *CPM*.3]

Pythagoras' theorem A mathematical result, concerning the lengths of the sides of a right-angled triangle, which states that: the square of the hypotenuse is equal to the sum of the squares of the other two sides. (The hypotenuse is opposite the right angle and is always the longest side.) [*DM*.2]

QCD See *quantum chromodynamics*. [*QPM*.4]

QED See *quantum electrodynamics*. [*QPM*.4]

***Q*-factor** A measure of the quality of a *damped oscillator*, calculated by dividing the total energy stored in the oscillator at any time by the energy lost per oscillation and multiplying the result by 2π, so

$$Q = \frac{2\pi \times \text{total stored energy}}{\text{average energy loss per oscillation}}.$$

A damped oscillator with a high Q-factor will complete many oscillations before most of its energy is dissipated. A low Q oscillator will complete very few. [*PM*.2]

quadratic equation Any equation that may be written in the form $ax^2 + bx + c = 0$ where a, b, c are constants and a is non-zero. [*DM*.2]

quadratic equation formula The formula

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

that determines the two solutions to any *quadratic equation* expressed in the form $ax^2 + bx + c = 0$. [*DM*.2]

quadratic function A function of the form $f(x) = ax^2 + bx + c$ with a, b and c all constants. [*DM*.1]

quadratic map A *map* in which each value has two possible predecessors. All quadratic maps exhibit chaos. [*PM*.5]

quantum An amount of energy associated with electromagnetic radiation of frequency *f*, equal to *hf* where *h* is *Planck's constant*. This is the amount of energy carried by a single *photon* of the radiation. [*QPI*.1]

quantum chromodynamics The *quantum field theory* of the *strong interaction*, so called because it involves the property known as *colour*. It is often abbreviated to QCD. [*QPM*.4]

quantum electrodynamics The *quantum field theory* of the *electromagnetic interaction*. It is often abbreviated to QED. [*RU*.1; *QPM*.4]

quantum field theory One of the major subdivisions of *quantum physics*, comparable to *quantum mechanics*. Quantum field theory is centrally concerned with fields, but allows them to be viewed as assemblies of field quanta, usually referred to as 'particles' (e.g. *photons*). The techniques of quantum field theory can be used to describe individual elementary particles, but are especially useful in situations that involve varying particle numbers, such as the emission and absorption of photons or the creation and annihilation of particle–antiparticle pairs. Quantum field theory provides a natural context for the formulation of quantum physical theories that accord with the principles of the *special theory of relativity*. Particular examples of such theories include *quantum electrodynamics*, *quantum chromodynamics* and the unified theory of the electroweak interaction. In practice, processes described by such theories are usually regarded as involving a number of intermediate states, the effects of which are calculated using Feynman diagrams which are constructed and evaluated according to a set of Feynman rules appropriate to the particular theory under consideration. [*RU*.1, *QPM*.4]

quantum gas Any gas of weakly interacting *indistinguishable* particles whose behaviour is influenced by their *boson* or *fermion* nature. Examples are the *photons* in *thermal radiation*, and the *free electrons* in a *metallic solid*. The translational energy of a quantum gas is not distributed in accordance with the *Maxwell–Boltzmann energy distribution*, except in the limiting case where the *de Broglie wavelength* is very much less than the typical distance between particles. Instead it is described by, for example, *Planck's radiation law* for photons and *Pauli's distribution* for free electrons. [*QPM*.1]

quantum-mechanical tunnelling See *tunnelling*. [*QPM*.3]

quantum mechanics One of the major subdivisions of *quantum physics*. Quantum mechanics is typically concerned with systems such as *nuclei*, *atoms*, *molecules* and *electrons* in solids, all of which have the feature that they may be treated as a finite number of interacting particles. Quantum-mechanical problems are often discussed in terms of a wave mechanical formalism which emphasizes the concept of a *wave function*, satisfying an appropriately formulated *Schrödinger equation*. [*RU*.1; *QPI*.2]

quantum numbers The numerical quantities that identify the possible *stationary state wavefunctions* of a quantum system. In the case of an electron in an atom, examples include the *principal quantum number* n, the *orbital angular momentum quantum number* l, and the *orbital magnetic quantum number* m_l. They are usually integers (apart from spin, s, which, for the electron, is equal to $\frac{1}{2}$). The possible values of the quantum numbers (apart from spin) are determined by finding the allowed solutions of *Schrödinger's equation*. [*QPI*.2]

quantum physics One of the major subdivisions of physics that should be compared and contrasted with *classical physics*. Quantum physics encompasses *quantum mechanics* and *quantum field theory*, along with a host of other quantum phenomena. Amongst its characteristic features are *indeterminacy* and the intrinsic use of *probability*, along with the appearance of *Planck's constant*. [*RU*.1]

quantum state The *state* of a *quantum system* defined with sufficient precision that it may be associated with a unique *wavefunction*. In the case of a *stationary state*, described by a *time-independent wavefunction*, it may be possible to specify the state in terms a unique set of *quantum numbers*. (If the system is a particle with *spin*, such as an electron in an atom, the relevant *spin magnetic quantum number* must be included.) Note that a quantum state is distinct from an *energy level*, which may correspond to several quantum states, all of which have the same energy, but different wavefunctions. (Such an energy level is said to be *degenerate*.) [*QPI*.2]

quantum system Any system which is analysed using the *formalism* of *quantum mechanics*. [*QPI*.4]

quark A term used to describe any of the charged particles that are currently believed to be fundamental constituents of all *hadrons* (i.e. *baryons* and *mesons*). Quarks are not expected to be observed as isolated particles due to *confinement*. Six kinds of quark are currently known (implying the existence of six kinds of antiquark). The six types are; *up* (u), *down* (d), *charm* (c), *strange* (s), *top* (t) and *bottom* (b). The quarks all have *spin* $\frac{1}{2}$, *baryon number* $\frac{1}{3}$, and a charge that is a multiple of $\frac{1}{3}e$. [*QPM*.4]

quasi-static process A process in which the *state* of a *system* changes so slowly that it effectively goes from one *equilibrium state* to another via a succession of intermediate equilibrium states. [*CPM*.1; *CPM*.3]

rad The standard abbreviation for *radian*. [*DM*.3]

radial coordinate The coordinate that measures distance from the origin in a *polar coordinate system*. [*DM*.3]

radial density function A function specifying the average number of particles per unit volume at a given distance from a chosen reference particle. Peaks and troughs in this function reveal *short-range order* in *liquids* and *long-range order* in *crystalline solids*. [*CPM*.1]

radial probability density The probability per unit length of finding a particle at a radial distance r from some specified point. When the (three-dimensional) *probability density* for finding the particle in the neighbourhood of the point is spherically symmetric about the point (as in the case of an s-state electron in an atom) the radial probability density is related to the *probability density* by

radial probability density

$$= 4\pi r^2 \times (\text{probability density})$$

$= 4\pi r^2 |\,\psi(r, \theta, \phi)\,|^2.$

The *probability* of finding such a particle in the narrow region between r and $r + \Delta r$ is $4\pi r^2 |\,\psi(r, \theta, \phi)|^2 \Delta r$. [*QPI*.3]

radian A unit of angle, common in scientific work. If a circular *arc* of length r has a radius r measured from a point O, then the angle subtended at O by the endpoints of the arc is 1 radian. It follows that 2π radians are equivalent to 360°, so 1 radian is equivalent to approximately 57.3°. The standard abbreviation of radian is rad. [*DM*.3]

radiation (a) Specifically, a mechanism of *heat* transfer in which *energy* is transferred from one body to another (possibly through a vacuum) by means of light or some other form of *electromagnetic radiation*. [*CPM*.3]

(b) More generally, a term used either as an abbreviation for *electromagnetic radiation* or when referring to particles emanating from a source (particularly those resulting from the radioactive decay of nuclei).

radiative transition A process in which a quantum system (such as an atom) undergoes a transition from one *energy level* to another by the emission or absorption of electromagnetic radiation (i.e. a *photon*). [*QPI*.3]

radioactivity The phenomenon whereby an unstable *nucleus* spontaneously decays and, as a consequence, emits *ionizing particles* or *electromagnetic radiation*. There are three main modes of radioactive decay: *α-decay*, *β-decay* and *γ-decay*; see those entries for further details. [*QPM*.3]

radio waves *Electromagnetic radiation* with a *wavelength* greater than around 10^{-1} m or a *frequency* less than about 3×10^9 Hz. [*DFW*.2]

radius of a nucleus The distance r from the centre of a *nucleus* at which the electric charge density $\rho_c(r)$ falls to one-half the value it has at the nuclear centre. For example, the radius of the ^{208}Pb nucleus is about 6.8 fm. [*QPM*.3]

radius of curvature (of a spherical mirror) The distance from the mirror's *centre of curvature* to its surface. It is equal to the radius of that sphere, part of whose surface constitutes the mirror. A *spherical mirror*'s *focal length* f is equal to half its radius of curvature, ρ, i.e. $f = \rho/2$. [*DFW*.3]

range The *distance* from the initial position of a *projectile* to the point at which the projectile ends its flight. [*DM*.2]

ratio of heat capacities The ratio $\gamma = C_P/C_V$ of the *molar heat capacities* at constant *pressure* and constant volume for a given quantity of a specified substance. For an *ideal gas* with f effective *degrees of freedom*, $\gamma = (f + 2)/f$, implying that γ is 1.67 for a *monatomic* ideal gas, 1.40 for a *diatomic* ideal gas and 1.33 for a *triatomic* ideal gas under moderate conditions. [*CPM*.3]

ray A directed line drawn perpendicular to a series of successive *wavefronts*. It can be thought of as giving the local direction of propagation of the *wave*. See *reversibility of light paths*. [*DFW*.2]

reaction A term used in *Newtonian mechanics* to describe one of the paired forces referred to in *Newton's third law of motion*, the other member of the pair being referred to as the *action*. [*PM*.1]

real image An image where the rays converge to, and pass through, the image points. Contrast with *virtual image*. [*DFW*.3]

real object An object from which *rays* diverge. Contrast with *virtual object*. [*DFW*.3]

realism The philosophical claim that there is a real world that humans have a common ability to perceive, but which exists independently of those perceptions. Philosophers recognize a number of variations on this basic theme. In the context of quantum mechanics, realism is that characteristic of a theory which implies that microscopic entities possess properties whether or not they are measured. [*RU*.1; *QPI*.4]

real-is-positive convention A consistent convention that can be used when calculating the relationships between the *focal length* of a *lens* or *mirror* and the corresponding *object* and *image distances*. According to this convention: *converging lenses* and *converging mirrors* have positive focal lengths, whereas *diverging lenses* and *diverging mirrors* have negative focal lengths; *real objects* and *real images* are assigned positive distance values, whereas *virtual objects* and *virtual images* have negative distance values; and the *lens equation* has the form $1/v + 1/u = 1/f$. [*DFW*.3]

recombination The process by which an *electron* in the *conduction band* of a *solid* falls to the *valence band* to fill an empty state or *hole* there, releasing an energy approximately equal to the *energy gap*. This energy appears in the form of lattice vibrations or, in a *light-emitting-diode*, as an optical *photon*. [*QPM*.2]

rectifier A device, usually consisting of a *p–n junction*, that allows an electric current to pass in one direction only. [*QPM*.2]

red giant A late stage in the evolution of a star, during which the star's surface temperature is somewhat lower (accounting for its redder colour) and its radius considerably larger (accounting for its giant status) than at most other stages. [*SFP*.2]

reductionism The proposal that observed phenomena can be explained in terms of more basic phenomena, until some level of fundamental entities and interactions is reached. (Contrast with *emergence*.) [*RU*.1]

reflecting telescope A *telescope* that uses a *mirror* as its *objective*. Also called a 'reflector'. (See also *Cassegrainian telescope*, *Newtonian telescope*, *Schmidt telescope* and *telescope*.) [*DFW*.3]

reflection The process whereby the *direction of propagation* of a *wave* travelling in a single medium, is changed as a result of its interaction with a boundary. When waves are reflected at a boundary they obey the *law of reflection*. [*DFW*.2]

refracting telescope A *telescope* that uses a *lens* as its *objective*. Also called a 'refractor'. (See also *Keplerian telescope*, *Galilean telescope* and *telescope*.) [*DFW*.3]

refraction The process whereby the *direction of propagation* of a *wave* passing from one medium to another, is changed as a result of its change of *speed*. When waves are refracted at a boundary between two media, they obey *the law of refraction* (*Snell's law*). [*DFW*.2]

refractive index The ratio of the *speed of light* in a vacuum to the speed of light in a particular medium; hence, refractive index $n = c/v$. The refractive index of a medium is always greater than one. (See also *law of refraction* (*Snell's law*)). [*DFW*.2]

refrigerator A device that uses externally supplied *work* to transfer *heat* from a cooler to a hotter body. [*CPM*.3]

relative atomic mass A numerical measure of the mass of a given species of *atom*, obtained by dividing the mass of the atom m by the *atomic mass unit*; so $M_r = m/1$ amu, where 1 amu is one-twelfth the mass of a carbon-12 atom. The relative atomic mass is a dimensionless quantity. [*CPM*.1]

relative molecular mass A numerical measure of the mass of a given species of *molecule*, obtained by dividing the mass of the molecule m by the *atomic mass unit*; so $M_r = m/1$ amu, where 1 amu is one-twelfth the mass of a carbon-12 atom. The relative molecular mass is a dimensionless quantity. [*CPM*.1]

relative permittivity An electrical property of an *insulator*, represented by the symbol ε_r. The relative permittivity of an insulator may be determined by dividing the *capacitance* of a *capacitor* when the insulator fills the region between the plates, by the capacitance of the same capacitor when its plates are separated by a vacuum. Relative permittivity is a dimensionless quantity. [*SFP*.2]

relative velocity The rate of change of the *displacement* of a particle or body from a specified reference point or body. Note that the chosen reference point or body is not required to be stationary. [*DM*.1]

relativistic collision A collision involving sufficiently high speeds that its analysis requires the use of the relativistic relations for momentum and energy rather than their Newtonian counterparts. Relativistic collisions are often *inelastic* and are characterized by the creation of new particles and an associated increase in *mass energy* (at the expense of *kinetic energy*). [*PM*.3]

relativistic energy The total *energy* of a body according to the *special theory of relativity*. For a free particle of (rest) mass m travelling with speed v

$$E = \frac{mc^2}{\sqrt{1-(v^2/c^2)}}.$$

The relativistic energy of such a particle is the sum of its *relativistic translational kinetic energy* and its *mass energy*. [*DFW*.4; *QPM*.4]

relativistic force The *force* acting on a body as determined by the rate of change of the *relativistic momentum* of the body. (See also *Newton's second law of motion*.) [*DFW*.4]

relativistic kinetic energy A term used occasionally as an abbreviation for *relativistic translational kinetic energy*. [*QPM*.4]

relativistic mechanics The branch of mechanics dealing with situations in which Einstein's *special theory of relativity* or *general theory of relativity* must be applied. [*DFW*.4]

relativistic momentum The *momentum* of a body according to the *special theory of relativity*. For a particle of (rest) mass m, travelling with velocity $\boldsymbol{v}$, the relativistic momentum is

$$\boldsymbol{p} = \frac{m\boldsymbol{v}}{\sqrt{1-(v^2/c^2)}}$$

At speeds which are small compared with the speed of light, c, this reduces to the Newtonian expression $\boldsymbol{p} = m\boldsymbol{v}$. [*PM*.3; *DFW*.4; *QPM*.4]

relativistic physics The branch of physics dealing with situations in which Einstein's *special theory of relativity* or *general theory of relativity* must be applied. [*DFW*.4]

relativistic translational kinetic energy The translational kinetic energy of a body according to the *special theory of relativity*. For a particle of *relativistic energy* E and *rest energy* E_0, the relativistic kinetic energy is $E - E_0$ and is therefore given by

$$E_{\text{trans}} = \frac{mc^2}{\sqrt{(1-v^2/c^2)}} - mc^2.$$

At speeds which are small compared with the speed of light, c, this reduces to the Newtonian expression $E_{\text{trans}} = mv^2/2$. [*DFW*.4 *QPM*.4]

relativity See *special theory of relativity* and *general theory of relativity*. [*DFW*.4]

relativity of simultaneity The phenomenon whereby two spatially separated *events* that are simultaneous according to one observer (i.e. happening at the same time in his/her *frame of reference*), may occur at two different times according to another observer, provided the second observer is moving relative to the first. (See also *causality* and *space–time conjunction*.) [*DFW*.4]

resistance The ratio R of the magnitude of the *potential difference* between the ends of a sample to the magnitude of the current flowing through that sample; $R = |V_R|/|i|$. In materials that obey *Ohm's law*, the resistance is constant, independent of the values of V_R or i. The *SI* unit of resistance is the *ohm* (Ω), where $1\,\Omega = 1\,\text{V A}^{-1}$. [*SFP*.3]

resistivity A measure of a material's ability to resist the flow of an electric current. If a uniform wire has *resistance* R, cross-sectional area A and length l, then the material from which it is made has resistivity $\rho = RA/l$. The resistivity of a material is a property of the material itself and is independent of the geometrical form or size of any particular sample of the material. The *SI* unit of resistivity is the Ω m. [*SFP*.3; *QPM*.2]

resistor An element in an electrical circuit whose main function is to provide electrical *resistance*. [*SFP*.3]

resolution The process of finding a vector's *components*, along specified directions, from the *magnitude* and direction of the *vector*. [*DM*.2]

resolving power of the eye The smallest angle of separation of two point-source objects at which the eye can still distinguish them as two distinct objects. [*DFW*.3]

resonance (a) In the context of a *driven damped oscillator*; resonance is the condition in which the oscillator develops oscillations of maximum amplitude for a given level of damping. For a lightly damped harmonic oscillator, this occurs when the driving

(angular) frequency Ω is close to the system's *natural frequency* ω_0. This is also close to the condition in which the rate at which energy is transferred to the oscillator by the driving force is a maximum. [*PM*.2]

(b) In the context of *particle physics*; a resonance is a very short-lived strongly interacting particle. See *hadron resonance* for further details. [*QPM*.4]

resonant frequency The value of the driving (angular) frequency of a driven damped harmonic oscillator that creates the condition of *resonance* in which the amplitude is a maximum for a given level of damping. [*PM*.2]

resonant photons *Photons* with an energy E that is exactly equal to the energy of a specified *radiative transition* in an atom. The photons are said to be resonant with the specified transition. [*QPI*.3]

response function A *function* that specifies how rapidly one property of a *macroscopic system* varies with respect to another under specified conditions. Response functions are usually defined in such a way that they characterize the material under study, and are independent of the shape and size of any particular specimen. Examples include the *isobaric expansivity* and the *isothermal compressibility*. [*CPM*.1]

rest energy The *relativistic energy* of a particle that is not moving. For a particle of (rest) mass m, the rest energy E_0 is given by $E_0 = mc^2$. Rest energy is also known as *mass energy*. [*QPM*.4]

rest mass The mass of a particle as measured by an *observer* relative to whom the particle is at rest. Associated with a given rest mass is a particular *mass energy*. [*DFW*.4]

restoring force A *force* tending to restore a body to some former position, often a position of equilibrium. Such a force acts in the direction opposite to the displacement of the particle from that former position. [*PM*.1]

resultant The vector obtained by combining two or more other vectors using the operation of *vector addition*. For example, if $\boldsymbol{s} = \boldsymbol{s}_1 + \boldsymbol{s}_2$ then $\boldsymbol{s}$ is the resultant of $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$. (See also *triangle rule*.) [*DM*.2]

resultant force The *force* obtained by combining two or more other forces using the operation of *vector addition*. When two or more forces act on a particle, their net effect is the same as that of their resultant force acting alone. [*PM*.1]

retina The photosensitive surface, on the inner wall of the eyeball, on which the eye focuses its images of the 'outside world'. [*DFW*.3]

reverse bias The condition in which an external voltage is applied across a *p–n junction* so as to increase the electric field in the *depletion layer* and suppress the *diffusion current* flowing across that layer. In reverse bias, the positive terminal of the external voltage source is connected to the *n-type* material and the negative terminal to the *p-type*. [*QPM*.2]

reversibility of light path The effect whereby reversing the direction of all the rays that indicate a particular light path results in another possible light path. That is to say, if a ray describes the path taken by light in propagating from A to B then the same ray, with its direction reversed, will also describe the path taken by light in propagating from B to A. [*DFW*.3]

reversible adiabat See *adiabat*, which has the same meaning. [*CPM*.3]

reversible adiabatic condition See *adiabatic condition*, which has the same meaning. [*CPM*.3]

reversible process A term used to describe a process where, following the completion of the process, both the *system* and its *environment* can be returned to the states they were in prior to the process. Any process that is not reversible is said to be irreversible. [*CPM*.3]

Reynolds number A dimensionless quantity characterizing the flow of a *fluid* and defined by

$$Re = \frac{\text{density} \times \text{characteristic speed} \times \text{characteristic length}}{\text{viscosity}}$$

[*CPM*.4]

right-handed coordinate system Starting with the palm of your right hand flat, extend the thumb so that it is approximately at right angles to the first finger, then bend the second finger so that it is at right angles to the plane of the palm. Your thumb, first and second fingers should then be mutually at right angles (at least approximately). A three-dimensional Cartesian coordinate system is said to be right-handed if, by rotation alone, it may be brought into alignment with the extended thumb, first and second fingers of your right hand in such a way that the z-axis points in the same direction as the thumb, the x-axis points in the direction of the first (index) finger, and the y-axis points in the direction of the second finger. Any three-dimensional Cartesian coordinate system that is not right-handed must be left-handed. [*DM*.2]

right-hand grip rule A rule for associating one of the two directions along an *axis* with a given sense of rotation about that axis. Extend the thumb of your right hand, and curl the fingers of that hand around the thumb. Then, turn your right hand so that its curled fingers twist around the thumb in the same sense that the rotation turns about the given axis. The direction along the axis indicated by your thumb is then the direction associated with the rotation. This rule may be used to associate the direction of an *angular velocity* with the rotation described by that angular velocity. Also, the rule may be used to associate the direction of *current* flow in a wire with the sense in which *magnetic field lines* circle around that wire. [*DM*.3; *SFP*.4; *DFW*.1]

right-hand rule A rule for determining the sense in which the vector product $\boldsymbol{a} \times \boldsymbol{b}$ is perpendicular to the vectors $\boldsymbol{a}$ and $\boldsymbol{b}$. The rule is the following: point the flattened palm and fingers of your right hand in the direction of vector $\boldsymbol{a}$. Then, keeping your palm and fingers parallel to $\boldsymbol{a}$, twist your wrist until you can bend your fingers to point in the direction of vector $\boldsymbol{b}$. Your extended thumb will then point in the direction of $\boldsymbol{a} \times \boldsymbol{b}$. [*PM*.4]

rigid body A body that can be regarded as a system of *particles* whose mutual separations remain fixed. In a rotating rigid body, all parts rotate at the same *angular velocity* $\boldsymbol{\omega}$ (i.e. at the same *angular speed* ω about the same *axis of rotation*). [*PM*.1]

rotational energy See *rotational kinetic energy*. [*CPM*.2]

rotational equilibrium The condition in which a system is free from any net external *torque*, so that

$$\sum_i \boldsymbol{\Gamma}_i = \mathbf{0}.$$

The *angular momentum* of such a system will be constant. [*PM*.4]

rotational kinetic energy The *kinetic energy* associated with the *rotational motion* of a body. For a body rotating with *angular speed* ω about a fixed axis, the rotational kinetic energy is

$$E_{\text{rot}} = \tfrac{1}{2} I\omega^2$$

where I is the body's *moment of inertia* about the axis of rotation. In the case of a *diatomic molecule* the rotational energy is associated with rotations of the molecule about axes perpendicular to the line joining the *atoms*. It does not include translational or vibrational contributions to the energy. [*PM*.4; *CPM*.2]

rotational motion A form of motion that involves turning about a line called the axis of rotation, and which should be contrasted with *translational motion*. (Any displacement of a *rigid body* may be regarded as arising from a translational motion of a point in that body together with a rotational motion about an axis passing through that point.) [*PM*.1]

Rutherford model of the atom The atomic model put forward by Ernest Rutherford, in which the electrons are assumed to orbit outside a tiny core or *nucleus* which contains all the positive charge and almost all the mass of the atom. [*QPI*.1]

Rydberg constant The Bohr model predicts that the wavelength of the *spectral line* emitted by a hydrogen atom when its electron makes a *radiative transition* from an *energy level* with Bohr *quantum number* n to an energy level with Bohr quantum number q is given by

$$\lambda_{n\to q} = \frac{1}{R}\left\{\frac{q^2 n^2}{n^2 - q^2}\right\}$$

where the constant R is known as the Rydberg constant. The value for R predicted by Bohr's theory

$$R = (1.096\,78 \times 10^7\,\text{m}^{-1})$$

agrees to within 6 parts in 10 000 with the experimentally measured value ($1.097\,37 \times 10^7\,\text{m}^{-1}$). [*QPI*.1]

satellite An object (possibly artificial) that moves in a closed *orbit* about an astronomical body such as the Earth. [*DM*.3]

scalar A quantity that is completely specified by a number, or a number multiplied by an appropriate unit of measurement. Scalar values can be positive, negative or zero. Examples include, distance, speed, mass. Electric charge and temperature. (Contrast with *vector*.) [*DM*.2; *SFP*.1]

scalar field A physical quantity to which a definite value can be ascribed at every point throughout some region of space. Examples include the temperature field in a room and the electric potential field between the plates of a capacitor. [*SFP*.1]

scalar product A product of two vectors $\boldsymbol{a}$ and $\boldsymbol{b}$, usually written as $\boldsymbol{a}\cdot\boldsymbol{b}$, and sometimes referred to as the 'dot product' of those vectors. Given two vectors $\boldsymbol{a}$ and $\boldsymbol{b}$, which are at an angle θ to each other, where $0° \le \theta \le 180°$, their scalar product $\boldsymbol{a}\cdot\boldsymbol{b}$ is defined by the relation

$$\boldsymbol{a}\cdot\boldsymbol{b} = ab\cos\theta.$$

Alternatively, if the components of $\boldsymbol{a}$ and $\boldsymbol{b}$ are such that $\boldsymbol{a} = (a_x, a_y, a_z)$ and $\boldsymbol{b} = (b_x, b_y, b_z)$ then the scalar product of $\boldsymbol{a}$ and $\boldsymbol{b}$ is given by

$$\boldsymbol{a}\cdot\boldsymbol{b} = a_x b_x + a_y b_y + a_z b_z.$$ [*PM*.2]

scale height A distance which characterizes the *exponential decay* of *pressure* with altitude in a *thin isothermal atmosphere*. (See *barometric formula*). When the altitude increases by the scale height, the pressure decreases by a factor of 1/e. [*CPM*.4]

scanning tunnelling microscope A type of microscope, in which a very fine, positively charged, metal tip is brought sufficiently close to the surface of the specimen that *electrons* can *tunnel* from the surface to the tip. By moving the tip across the surface of the specimen in such a way that the tunnelling current remains constant, the surface topography is mapped out. Under favourable circumstances, it is possible to deduce the locations of surface *atoms*. [*CPM*.1]

Schmidt camera A *Schmidt telescope* which has a photographic detector at the *prime focus* of the *objective mirror* in order to capture a *real image*. Such devices typically have an undistorted image over a large *field of view*. [*DFW*.3]

Schmidt plate A glass plate used to introduce a predistortion into parallel *wavefronts* in order that they can be focused to a single point by a *spherical mirror*. The effect is therefore to greatly reduce the effects of *spherical aberration*. A *reflecting telescope* utilizing a Schmidt plate is referred to as a *Schmidt telescope*. [*DFW*.3]

Schmidt telescope A *reflecting telescope* that utilizes a *Schmidt plate* to overcome the *spherical aberration* of a *spherical mirror*. [*DFW*.3]

Schrödinger's cat A hapless beast enclosed in a box along with a radioactive *nucleus* and a fiendish device that will break open a phial of poison gas when the decay of the nucleus is detected. This set-up was introduced into *quantum physics* by Erwin Schrödinger to highlight the difficulties of making sense of macroscopic *superposition* states such as the *state* in which the cat has some probability of being alive and some probability of being dead. (See also *decoherence effect*.) [*QPI*.4]

Schrödinger's equation See *time-dependent* and *time-independent Schrödinger's equation*.

second The *SI* unit of *time*, represented by the symbol s. The second is one of the seven SI *base units*, and is defined as 9192 631 770 periods of a certain kind of electromagnetic radiation emitted by caesium-133 atoms. [*DM*.1]

secondary mirror A relatively small mirror used in a *reflecting telescope* to direct the light after it has been reflected from the *objective mirror* (or *primary mirror*). In a *Newtonian telescope*, the secondary mirror is a *plane mirror* inclined at 45° to the *optical axis*. In a *Cassegrainian telescope*, the secondary mirror is a *diverging mirror* perpendicular to the optical axis, and

serves to extend the *effective focal length* of the telescope. [*DFW*.3]

second derivative The *derivative* of the derivative of a *function*. Given a function $f(y)$, its second derivative with respect to y is also a function of y, and may be written as $\dfrac{d^2 f(y)}{dy^2}$. [*DM*.1]

second law of thermodynamics A law stating that; in the neighbourhood of any *equilibrium state* of a *macroscopic system* there are states that are *adiabatically inaccessible* (Carathéodory's version.)

Or: the *entropy* of the *Universe* tends to a maximum. (Boltzmann's version.)

Or: no *cyclic process* is possible which has, as its sole result, the complete conversion of a positive quantity of *heat* into *work*. (Kelvin's version.)

Or: no *cyclic process* is possible which has, as its sole result, the transfer of a positive quantity of *heat* from a cooler body to a hotter one. (Clausius's version.)

Any of these may be used to justify the introduction of a *function of state* known as *entropy*, that never decreases in any *isolated system*. It thereby provides the basis for the general *principle of entropy increase*. [*RU*.1; *CPM*.3]

second-order differential equation A *differential equation* involving a *second derivative* but no higher derivative. [*DM*.3; *PM*.1]

seismic wave A wave in the Earth, generated by an earthquake. P-(primary) waves are *longitudinal waves*, whereas S-(secondary) waves are *transverse waves*. [*DFW*.2]

selection rules Rules that govern whether particular *radiative transitions* are *allowed* or *forbidden*. For example, the allowed changes in the *quantum numbers* of an electron in an atom are restricted to $\Delta l = \pm 1$ and $\Delta m_l = 0$ or ± 1. There is no restriction on the change in the value of n. [*QPI*.3]

self-inductance See *coefficient of self-inductance*. [*DFW*.1]

self-induction The phenomenon whereby changes to the *electric current* flowing in a coil (or any other circuit element) are hampered by the *self-inductance* of the coil. Changing the current in a coil creates a changing *magnetic field* in the space in and around that coil. This changing magnetic field will give rise to a changing *magnetic flux* through the coil; and this, by *Faraday's law*, will create an *EMF* in the coil. By *Lenz's law*, the direction of this *induced EMF* will be such that it opposes the original current change that caused it. Changes in current are therefore 'opposed' and the extent of the opposition will depend on the coil's self inductance, which determines the magnitude of the induced EMF produced by a given rate of change of current in the coil. [*DFW*.1]

semiconductor A material with an *energy gap* between the *valence band* and the *conduction band* of between about 0.1 eV and 3 eV. Such a material is an *insulator* at very low temperatures, but conducts electricity near room temperature, and typically has a room temperature *electrical conductivity* between about 10^{-4} and $10^{2}\,\Omega^{-1}\,m^{-1}$. [*QPM*.2]

semi-empirical model A model of the atomic *nucleus* that attempts to provide insight into the systematic behaviour of nuclei in general on the basis of a mixture of empirical measurements of nuclear radii and *binding energies*, and an analogy between an atomic nucleus and a water droplet. (See also *Coulomb energy, surface energy* and *volume energy*.) [*QPM*.3]

semimajor axis A line segment from the centre of an *ellipse* to a point on the ellipse, such that the line has the maximum possible length. [*DM*.3]

semiminor axis A line segment from the centre of an *ellipse* to a point on the ellipse, such that the line has the minimum possible length. [*DM*.3]

shell A specified collection of *electrons* in an *atom*. In the Bohr model of the atom, each shell consists of electrons moving in *Bohr orbits* that correspond to a particular value of Bohr's *quantum number*, n. In Schrödinger's *quantum-mechanical* model, each shell is composed of electrons in *stationary states* that correspond to a common value of the *principal quantum number*, n. [*QPI*.3]

s.h.m. See *simple harmonic motion*.

short-range order The phenomenon exhibited by some forms of matter, particularly *liquids* and *amorphous solids*, in which the near neighbours of a typical atom show some signs of regularity and order in their spatial arrangement, but that order does not extend beyond those near neighbours. (Contrast with *long-range order*, and see also *radial density function*.) [*CPM*.1]

short-sightedness A defect of vision in which the *far point* of the eye is considerably closer than infinity (and the near point much closer than the *normal near point* of 250 mm). As a result the eye is unable to focus on distant objects (the eye is too strong, and light from an object located further away than the far point would be focused in front of the retina). Short-sightedness is known technically as *myopia*. (See also *presbyopia*.) [*DFW*.3]

shutter A mechanism that can be opened and closed for a predetermined length of time so as to control the light entering a *camera* body to expose the *film*. [*DFW*.3]

shutter-speed A (somewhat colloquial) term used to describe, in effect, the length of time for which a camera's *shutter* is open. It is usually expressed as the reciprocal of the 'open time'; for example, a shutter speed of 60 means that the shutter is open for 1/60 s. [*DFW*.3]

SI An internationally agreed system of units of measurement. The system employs seven *base units* (including the *metre* and the *second*) and an unlimited number of derived units obtained by combining the base units in various ways. The system also uses certain standard *SI multiples* and *SI submultiples* and recognizes a number of standard symbols and abbreviations. (SI is one of those symbols and stands for Système International.) [*DM*.1]

sigma particle A kind of *elementary particle*. A *strange baryon* with *spin* $\frac{1}{2}$, and a mass that is about 25% greater than that of the proton. There are three

kinds of sigma particle, indicated Σ^+, Σ^-, Σ^0 according to charge. [*QPM*.4]

signed area under a graph The area bounded by the curve of a *graph*, the horizontal *axis* and two vertical lines drawn from specified values on the horizontal axis. A positive sign is given to an area above the horizontal axis and a negative sign to an area below the horizontal axis. Note that the area is expressed in terms of the units used on the axes, *not* in terms of the physical area of paper. [*DM*.1]

significant figures The accurately meaningful digits in the value of a physical quantity. The number of significant figures in a value such as 12 000 may be ambiguous unless the value is expressed in *scientific notation*, in which case 1.2×10^4 would indicate 2 significant figures, whereas 1.2000×10^4 would indicate 5 significant figures.

silver halide A generic term used to describe the group of salts in which silver is combined with an element from the halogen group (namely, fluorine, chlorine, bromine, iodine). Photographic *emulsions* commonly use one of the silver halides AgCl (silver chloride), AgBr (silver bromide) or AgI (silver iodide) as the photosensitive agent. [*DFW*.3]

simple gas model A model of a *gas* that treats the *molecules* of the gas as structureless *particles* in random motion. The molecules collide with one another and with the walls of their container, subject to the laws of *Newtonian mechanics*. Gravity and intermolecular forces between collisions are neglected and all collisions are taken to be *elastic*. [*CPM*.2]

simple harmonic motion A particular form of oscillatory motion about a specified *equilibrium position*, characterized by the fact that the *acceleration* is always directed towards the equilibrium position and is proportional to the *displacement* from that point. In one dimension, any simple harmonic motion may be described by an equation of the form

$$d^2x(t)/dt^2 = -\omega^2 x(t)$$

which has the *general solution* $x(t) = A\sin(\omega t + \phi)$, where A is the *amplitude* of the motion, ω is its *angular frequency*, and ϕ is the *phase constant* (or initial phase) of the motion. [*DM*.3]

simple harmonic motion equation The *second-order differential equation*

$$d^2x(t)/dt^2 = -\omega^2 x(t)$$

which has the *general solution* $x(t) = A\sin(\omega t + \phi)$. [*DM*.3]

simple microscope See *magnifying glass*. [*DFW*.3]

simple pendulum A weight (also known as a *bob*) suspended by a light inelastic string. [*DM*.3]

simple solid model A model of a *solid* in which independent *atoms* oscillate in three dimensions about fixed *equilibrium positions*. [*CPM*.2]

simultaneity See *relativity of simultaneity*. [*DFW*.4]

SI multiple Any one of a number of standard factors of the form 10^3, 10^6, 10^9, etc. Each is represented by a standard prefix such as kilo, mega, giga, etc. [*DM*.1]

sine function See *trigonometric functions*. [*DM*.3]

single-slit diffraction pattern The characteristic pattern of illumination (featuring well-defined maxima and minima of intensity) obtained when a single slit of width w is illuminated normally with *plane waves* of *wavelength* λ. The first minimum in the pattern occurs at an angle θ to the incident beam, where $\sin\theta = \lambda/w$. [*DFW*.2]

sinusoidal A term indicating a variation that may be described by a sine function. This also applies to a cosine function since $\cos(\theta) = \sin(\theta + \pi/2)$. [*DM*.3]

SI submultiple An SI submultiple is one of a number of standard factors of the form 10^{-3}, 10^{-6}, 10^{-9}, etc. Each is represented by a standard prefix such as milli, micro, nano, etc. [*DM*.1]

slope of a graph See *gradient of a graph,* which is a synonym. [*DM*.1]

Snell's law See *law of refraction*. [*DFW*.2]

soft magnetic behaviour The behaviour of magnetic materials that lose much of their *magnetization* when the applied *magnetic field* responsible for that magnetization is removed. Such materials are generally easy to magnetize, but their magnetization does not persist. [*SFP*.4]

solar cell A large area *p–n junction* used to generate electrical power by absorbing energy from light, normally sunlight. [*QPM*.2]

solar wind A continuous (though not steady) stream of charged particles, mostly protons and electrons, emanating from the Sun. The solar wind helps shape the Earth's *magnetosphere*. [*SFP*.4]

solid A phase of *matter* which exhibits rigidity, and is not able to flow. The *atoms* or *molecules* in a solid oscillate around fixed equilibrium positions. In a *crystalline solid*, the atoms exhibit *long-range order*. [*CPM*.1]

solid state A term used to describe any electronic circuit or device containing solid-based (usually silicon) *semiconductors*. The term is also used to describe the field of physics in which the properties of solids are studied. [*QPM*.2]

solution (of an equation) Any value which, when substituted into a given equation, turns that equation into a true identity. For example, $x = 2$ is a solution of the equation $3x = 4 + x$ because 3×2 is identical to $4 + 2$. The idea of a solution may be extended to other types of equation, including *differential equations*, where the solution takes the form of a *function*. (See also *quadratic equation formula*, and, in the context of differential equations, *general solution*.) [*DM*.2]

sound wave A *longitudinal wave* with a *frequency* between about 20 Hz and 20 000 Hz, that might be the direct cause of the phenomenon perceived as sound. Such waves can travel through a gas, liquid or solid. [*DFW*.2]

space The collection of all possible *positions*. [*DM*.2]

space–time conjunction Two events that occur together in space *and* time. All observers will agree that the events constitute a conjunction, though different observers may assign different coordinates to that conjunction. [*DFW*.4]

special relativity See *special theory of relativity*. [*DFW*.4]

special theory of relativity The theory, proposed by Albert Einstein in 1905, that relates the observations made by different *inertial observers* who are in *uniform relative motion*. (This restriction to uniform relative motion is what accounts for the use of the term 'special' in the name of the theory.) The theory is based on *Einstein's postulates*, the first of which, the *principle of relativity*, asserts that the laws of physics can be written in the same form in all *inertial frames of reference*, while the second, the principle of the constancy of the speed of light, asserts that the speed of light (in a vacuum) has the same constant value in all inertial frames of reference. At the heart of the special theory of relativity are the *Lorentz transformations*, that relate the coordinates (x, y, z, t) of an *event* in a specified inertial frame, to the coordinates (x', y', z', t') of the same event in some other inertial frame. The consequences of this relationship include the effects referred to as *Lorentz contraction* and *time dilation*, as well as modified expressions for *translational kinetic energy* and *linear momentum*. It also gives rise to the idea of *mass energy* embodied in the most famous equation in all of physics, $E = mc^2$. *Maxwell's equations* already obey Einstein's theory without the need for modification; *electromagnetic induction* by motion arises directly from the application of the Lorentz transformation to Maxwell's equations. The predictions of the special theory of relativity have been extensively supported by experiments performed to test their validity. [*RU*1; *DFW*.4]

specific heat capacity The *heat capacity* per unit mass of a specified substance. In other words, the energy per unit mass and per unit temperature rise needed to raise the temperature of a sample of a specified substance under specified conditions (such as constant *pressure* or constant volume). Specific heat capacity is measured in units of $\mathrm{J\,K^{-1}\,kg^{-1}}$, and is often referred to simply as 'specific heat'. [*CPM*.3]

spectra The plural of *spectrum*.

spectral lines Narrow lines seen in the *spectrum* of a substance. The lines correspond to those particular *wavelengths* of *electromagnetic radiation* that may be absorbed or emitted by *atoms* or *molecules* of the substance as a result of *transitions* occurring between *energy levels*. (See also *spectrometer*.) [*QPI*.1]

spectrometer A device that uses a *diffraction grating* (or prism) to spread the light from a source into its constituent *wavelengths*, thus producing a spectrum that can be examined and measured. Measurements of the *spectral lines* seen in such a *spectrum* can greatly assist the analysis of the material from which the light originated, or any material through which the light has passed on its way to the spectrometer. [*DFW*.2]

spectroscopic notation A notation in which the value of the *orbital angular momentum quantum number* of an electron in an atom is labelled by a letter, namely: $l = 0$ states are labelled s; $l = 1$ states p; $l = 2$ states d; $l = 3$ states f; $l = 4$ states g, and thereafter letters are used alphabetically for increasing l. The *principal quantum number n* is written explicitly as a number before the letter denoting the value of l. Thus

3s is spectroscopic notation for $n = 3$, $l = 0$

4d is spectroscopic notation for $n = 4$, $l = 2$. [*QPI*.3]

spectroscopy The study of *spectra*, particularly for the purposes of chemical analysis. It was an area of much scientific activity in the second half of the nineteenth century. Its techniques were further extended and refined throughout the twentieth century and remain crucial to chemical analysis and to many other areas of physical investigation. [*QPI*.1]

spectrum (a) In the context of the *electromagnetic radiation* emitted by *atoms* or *molecules*; a spectrum is any detailed representation of the way in which the intensity of the radiation is distributed with respect to *wavelength* or *frequency*. A spectrum may be obtained experimentally, as a band of light, using a *spectrometer* or some similar instrument. Alternatively the spectrum may be presented as a *graph*.

(b) In more general contexts; the term spectrum may be used to refer to any spread or distribution of one quantity with respect to another.

specular reflection If a particle bounces off a planar surface at the same angle as it approached the surface, it is said to have undergone specular reflection. [*CPM*.2]

speed (a) In the context of *kinematics*; the speed of a specified body is the *magnitude* of the (instantaneous) *velocity* of that body. The *SI* unit of speed is the metre per second ($\mathrm{m\,s^{-1}}$). [*DM*.1; *DM*.2]

(b) In the context of *waves*; the speed v of a *travelling wave* is the product of the *wavelength* λ and *frequency* f of the wave, so $v = f\lambda$. (This also represents the speed at which a point of constant *phase* travels in the *direction of propagation* of the wave, and may therefore be referred to as the 'phase speed' of the wave.) The *speed of light* in a vacuum is represented by the symbol c and has a value of $3.00 \times 10^8\,\mathrm{m\,s^{-1}}$. [*DFW*.2]

speed distribution function A function $f(v)$ which, when multiplied by a small range of speeds, Δv, indicates the fraction $f(v)\Delta v$ of some specified population of particles with speeds between v and $v + \Delta v$. The speed distribution function for a classical gas is given by the *Maxwell–Boltzmann speed distribution*. [*CPM*.2]

speed histogram A histogram in which the height of each bar is proportional to the fraction of particles with speeds within the width of the bar. [*CPM*.2]

speed of light The speed at which all *electromagnetic radiation* propagates. In a vacuum it is represented by the symbol c and has a value $3.00 \times 10^8\,\mathrm{m\,s^{-1}}$ (to three significant figures). In other media, the speed of light is less than c, and is often different for different *frequencies* of radiation, so giving rise to the phenomenon of *dispersion*. Einstein's *special theory of relativity* is based on the postulate that the speed of light (in a vacuum) has the same constant value in all *inertial frames of reference*; that is, it is *not* the speed relative to a fictitious *ether*, nor is it the speed with respect to the source of radiation. *Causality* in Einstein's theory relies on the fact that the speed of light in a vacuum is the maximum speed at which a signal can travel. [*DFW*.2; *DFW*.4]

speed–time graph A *graph* showing the *speed* of a body (plotted vertically) against time (plotted horizontally). [*DM*.1]

spherical aberration The blurring of the image produced by a *spherical lens* or *spherical mirror* and caused by the fact that rays further away from the *optical axis* are focused more strongly than rays close to the axis. *Parabolic mirrors*, in which the mirror surface has a parabolic rather than spherical shape, are frequently used to eliminate spherical aberration in large *telescope* mirrors. Alternatively, a *Schmidt plate* may be used to introduce a predistortion in the incident *wavefront* in order to counteract spherical aberration. [*DFW*.3]

spherical lens A *lens* whose surfaces are parts of spheres. Contrast with *cylindrical lens*. [*DFW*.3]

spherical mirror A mirror whose surface shape is part of the surface of a sphere. Contrast with *parabolic mirror* and *plane mirror*. [*DFW*.3]

spherical polar coordinate system A *coordinate system* in which the position of a point is given by the three coordinates (r, θ, ϕ) where r is the distance from the origin, θ is the angle that the position vector $\boldsymbol{r}$ of the point makes to the z-axis, and ϕ is the angle between the x-axis and the projection of $\boldsymbol{r}$ on to the xy-plane. This coordinate system is particularly useful for systems that exhibit *spherical symmetry,* since the quantities associated with that system depend only on r and not on θ or ϕ. [*QPI*.3]

spherical symmetry The characteristic of a system whereby some property (e.g. its density) depends only on the distance from a specified point (usually the centre of the system). [*PM*.1; *QPI*.3]

spherical wave A *wave* that spreads out isotropically from a fixed source, with spherical wavefronts. The *intensity* of a spherical wave obeys an *inverse square law*. [*DFW*.2]

spherical wavefront A *wavefront* produced by a *spherical wave*. Such a wavefront takes the form of a spherical surface and connects points in the (spherical) wave that have the same phase. [*DFW*.2]

spin See *spin angular momentum quantum number*. [*QPI*.3; *QPM*.4]

spin angular momentum quantum number A *quantum number*, conventionally represented by the symbol s, that characterizes the magnitude S of the intrinsic *angular momentum* of a particle:

$$S = \sqrt{s(s+1)}\,\hbar\,.$$

The spin angular momentum quantum number is often referred to as simply the *spin*; hence the electron is said to have spin $\frac{1}{2}$, and the photon spin 1. Spin is an inherently quantum property. [*QPI*.3; *QPM*.4]

spin magnetic quantum number A *quantum number*, conventionally represented by the symbol m_s, that determines the z-component, S_z, of the intrinsic *angular momentum* of a *particle*:

$$S_z = m_s\hbar.$$

For a particle with *spin* $s = \frac{1}{2}$ (such as an *electron*) m_s can take only two values, $\pm\frac{1}{2}$; for a particle with spin 1 (such as a *photon*), m_s can take the values, ±1 or 0. [*QPI*.3]

spinning top A disc (or other heavy axially symmetric object) mounted on an axle. One end of the axle is pointed and acts as a *pivot* about which the entire object can rotate. [*PM*.4]

spin–orbit interaction The interaction between the *magnetic moments* associated with the *spin* and *orbital angular momentum* of each *electron* in an *atom*. The spin–orbit interaction gives rise to splittings in the atomic *energy levels* due to the fact that the *potential energy* of the interaction is positive when the two magnetic moments are aligned parallel to each other and negative when they are antiparallel. [*QPI*.3]

spontaneous emission The process whereby the *emission of radiation* from an *atom* in an *excited state* occurs spontaneously, without interaction with other atoms or with incident *photons*. Spontaneous emission from atoms in a specified *excited state* occurs randomly and in such a way that a population of those atoms will decay *exponentially* with a characteristic *time constant*. [*QPI*.3]

spontaneous fission A form of *radioactivity* with a very long *half-life* by which some heavy nuclei such as ^{238}U split into two roughly equal fragments and a few *neutrons*, with the release of energy. [*QPM*.3]

spring constant The *constant of proportionality* k_s between the *restoring force* F_x and the extension x for an *ideal spring* that obeys *Hooke's law*; $F_x = -k_s x$. [*PM*.1]

square The square of a quantity is the result of multiplying the quantity by itself, for example

$$x^2 = x \times x. \quad [DM.1]$$

square root rule A rule asserting that; if our best estimate is that a certain outcome will occur N times, we should expect fluctuations of order $\sqrt{N}$, but we should be astonished if the outcome occurred less than $N-10\sqrt{N}$ times or more than $N+10\sqrt{N}$ times. [*CPM*.2]

SQUID An acronym for Superconducting Quantum Interference Device. Such a device typically consists of two *Josephson junctions* connected *in parallel*, and may take the form of a loop of *superconductor* interrupted by two 'weak link' point contacts. The electric *current* that flows in the loop is extremely sensitive to changes in the *magnetic flux* through the loop, so a SQUID can be used to detect tiny changes of *magnetic field*. [*QPM*.2]

stable equilibrium A type of *static equilibrium* in which a system displaced slightly from its original position has a tendency to return to that position. This is the kind of static equilibrium exhibited by a uniform spherical body resting at the bottom of a hollow. [*PM*.4]

standard configuration The simplest possible arrangement of two *inertial frames of reference* with constant velocity relative to each other. The axes of the first *frame of reference* are all parallel to the corresponding axes of the second frame of reference. The origins of the two frames of reference coincide at $t = t' = 0$, and the origin of the second frame of reference moves along the x-axis of the first in the positive direction. The two frames of reference maintain the same relative orientation while moving. [*DFW*.4]

standard model A *quantum field theory* that incorporates fields representing the twelve fundamental *quarks* and *leptons* and the *exchange particles* of the *strong*, *weak* and *electromagnetic interactions*. It is well supported by current particle physics data. [*QPM*.4]

standard notation One of the two common ways of writing down the *electronic structure* of an atom (the other being *box notation*). In standard notation, the structure is given using *spectroscopic notation* and the number of electrons occupying each *subshell* is indicated by a superscript. For example, in standard notation the *ground state* of carbon is written as

$$\mathrm{C} \quad 1s^2\,2s^2\,2p^2 \qquad [QPI.3]$$

standing wave A *wave* that does not travel, although it can be regarded as being the *superposition* of two *travelling waves*, travelling in opposite directions. Along the path of the wave there are regularly spaced points, called *nodes*, at which the wave causes no disturbance; these nodes are separated by half a *wavelength.* At all points between the nodes *oscillations* occur at a common *frequency* but with differing *amplitudes*. A common example of a standing wave arises in the case of a string stretched between fixed endpoints (as in a musical instrument); the standing waves that can be excited on such a string are restricted by the requirement that an integer number of half-wavelengths must fit between the endpoints, where the disturbance is zero. [*DFW*.2]

state The condition of a system, described in sufficient detail to distinguish it from other conditions that would behave differently. In *classical physics* the state of a system may be specified by listing the values of various observable quantities (e.g. the pressure and temperature of a given quantity of ideal gas). In *quantum mechanics*, the state of a system is specified by its *wavefunction*, and the meaning of 'behave differently' must encompass the *indeterminacy* and *indeterminism* of quantum mechanics. [*CPM*.3; *QPI*.4]

state space An abstract 'space' in which the *state* of a (classical) *system* may be represented by a point. If m quantities are required to completely specify the state of a system, then the corresponding state space is m-dimensional and the point in state space that represents any given state of the system will have m coordinates. The changing state of a system as it evolves with time can be represented by a trajectory in state space. [*PM*.5]

state variable The term used to describe any property of a *system* that depends only on the *equilibrium state* of the system, and not on how that equilibrium state was reached. (See *function of state*.) [*CPM*.3]

static equilibrium A special case of *mechanical equilibrium* in which a body is completely at rest. For such a body the net external *torque* about any point must be zero. [*PM*.4]

statics The branch of *dynamics* that deals with systems at rest. [*PM*.4]

stationary state A *quantum state* in which the *probabilities* of all the possible outcomes of measurements are independent of time. Although such states may be described by time-dependent wavefunctions $\Psi(x, t)$, they are, for most purposes, adequately described by a *time-independent wavefunction* $\psi(x)$. In practice, such states are often specified in terms of the values of the *quantum numbers* that characterize that state. A typical example would be the state of the hydrogen atom specified by the quantum numbers $n = 2$, $l = 1$, $m_l = -1$. [*QPI*.2]

statistical mechanics The branch of physics that explains and predicts the behaviour of (large-scale) *macroscopic* systems in terms of the statistical behaviour of their *microscopic* constituent particles. Statistical mechanics uses the methods of *probability* theory and statistical analysis to predict the likely behaviour of the constituent particles, and relies on the fact that, in a system containing a vast number of particles, such 'likely' behaviour is practically certain to happen. [*RU*.1; *CPM*.2]

stimulated absorption An alternative term for the process known simply as *absorption* in which an *atom* absorbs a *photon* as an electron within the atom makes a transition from a lower *energy level* to a higher energy level. [*QPI*.3]

stimulated emission The process whereby the *emission of radiation* from an *atom* in an *excited state* occurs as a result of its interaction with incident *electromagnetic radiation.* If the excited state of the atom is such that an electron can make a *radiative transition*, of energy E, to a state of lower energy, then, incident *photons* of energy E, can stimulate the excited atom to emit a photon of energy E. This process occurs with a much greater probability than the process of *spontaneous emission* which can take place in the absence of incident photons. The emitted photon is in the same *quantum state* as the incident photon. In terms of waves, the emitted radiation has the same *frequency* and *phase* as the incident radiation and it travels in the same direction. The process of stimulated emission allows the construction of *lasers*. [*QPI*.3]

Stokes' law A law stating that; when a sphere of radius R moves through a fluid at constant speed v, the *magnitude* of the *viscous force* that opposes the motion is

$$F = 6\pi\eta Rv$$

where η is the *coefficient of viscosity* of the fluid. [*PM*.1]

stop See *aperture stop*. [*DFW*.3]

stopping potential The value of the retarding potential which just stops the flow of photoelectrons in an experiment to verify Einstein's theory of the *photoelectric effect*. [*QPI*.1]

strain energy An abbreviation for *strain potential energy*. [*PM*.2]

strain potential energy The *potential energy* of a stretched body subject to *conservative restoring forces*; i.e. the *work* done by those forces in returning the body to its unstretched configuration. In the case of an *ideal spring* extended by an amount x from its unextended state, the strain potential energy is given by

$$E_{\text{str}} = \tfrac{1}{2}k_s x^2. \quad [PM.2]$$

strange attractor A region of *state space* into which trajectories are attracted, and within which they exhibit *chaotic* behaviour. [*PM*.5]

strangeness A property of *hadrons* that is in some respects similar to *electric charge* or *baryon number*. Strangeness is conserved in *strong* and *electromagnetic interactions*, but not in *weak interactions*. [*QPM*.4]

strange particle A particle that possesses a non-zero value of *strangeness*. Examples include the *kaons* (K^+, K^-, K^0, $\overline{K}^0$), the *lambda* (Λ^0), the *sigmas* (Σ^+, Σ^-, Σ^0) and the *xi* or *cascade particles* (Ξ^-, Ξ^0). [*QPM*.4]

strange quark One of the six types of *quark*. It is the only quark to have non-zero *strangeness*. [*QPM*.4]

streamline The path of a particle in a *fluid*. [*CPM*.4]

strings Hypothetical extended objects that are consistent with quantum theory and involve *supersymmetry*. It was hoped that they would provide a plausible *superunified theory*. [*QPM*.4]

stroboscopic (photography) A technique for recording the motion of an object. As the object moves, a rapid sequence of short-duration flashes enables a camera to record several successive positions of the object on a single photographic image. [*DM*.2]

strong force See *strong nuclear force*.

strong interaction See *strong nuclear force*. [*QPM*.4]

strong nuclear force A very short-range attractive force (also called the *strong force* or the *strong interaction*), that acts between *nucleons*. It does not act on *electrons* or other *leptons* and is almost independent of electric charge. The strong nuclear force is responsible for holding the *nucleus* together, despite the mutual electrostatic repulsion of its constituent protons. The strong nuclear force is the strongest of the four *fundamental forces*. [*RU*.1; *QPM*.3; *QPM*.4]

subject A *variable* isolated on one side (usually the left-hand side) of an equation, and therefore expressed in terms of the other variables in the equation. [*DM*.1]

subshell Any collection of *electrons* in an *atom*, occupying *stationary states* that correspond to common values of the *principal quantum number*, n, and of the *orbital angular momentum quantum number*, l. [*QPI*.3]

subtend A term used to describe the relation between two points (or an arc connecting those points) and the angle between those points as measured at a third point. A circular arc of radius R and arc length s_{arc} is said to subtend an angle (measured in radians) of $\alpha = s_{\text{arc}}/R$ at the centre of the circle of which it is part. More generally, any two points A and B may be said to subtend an angle α at a third point C if α is the *angular displacement* of A from B, as measured at C. [*DM*.3]

superconducting energy gap A characteristic amount of *energy* that separates the *ground state* of a *superconductor* from the lowest *excited state*. The *BCS theory* predicted the existence of this superconducting energy gap, and that its value would depend strongly on temperature, rising from 0 J at the *superconducting transition temperature* T_C to about $3.5kT_C$ at *absolute zero*. The experimental confirmation of these predictions gave early support to the BCS theory. The energy gap is, in effect, the binding energy of a *Cooper pair*. [*QPM*.2]

superconducting transition temperature The maximum temperature T_C at which a material can display *superconductivity*. For temperatures below T_C the electrons form *Cooper pairs*, becoming fully paired at 0 K. The pairing is gradually destroyed by thermal agitation as the temperature rises towards T_C. [*QPM*.2]

superconductivity The phenomenon exhibited by a number of materials, whereby, at a sufficiently low temperature, the *resistivity* becomes zero (i.e. the *electrical conductivity* becomes infinitely large) and *magnetic flux* is expelled. [*QPM*.2]

superelastic collision A collision in which the *kinetic energy* increases, typically as a result of the release of *potential energy*. [*PM*.3]

supernova An extremely violent stellar explosion that causes a star to suddenly flare up in brightness and then gradually fade again over a period of (typically) a year or so. The explosion occurs when a massive *red giant* star runs short of fuel and collapses under its own gravity. During the collapse, nuclear reactions convert *electrons* and *protons* into *neutrons* and *neutrinos*. As a result, apart from leaving behind an expanding cloud of gas known as a ‘supernova remnant’, a supernova can also lead to the formation of a *neutron star*. [*SFP*.2]

superposition See *principle of superposition*. [*DFW*.3]

supersymmetry A proposed symmetry, involving elementary particles and their interactions, that suggests hitherto unconfirmed relationships between *fermions* and *bosons*. Supersymmetry has been used in formulating a number of *superunified theories* of particle physics. If supersymmetry really is a symmetry of nature, then it implies the existence of several new types of elementary particles. [*QPM*.4]

superunified theories *Quantum field theories* that attempt to unify all four *fundamental interactions*. No satisfactory self-consistent theory exists at present. [*QPM*.4]

surface energy A contribution to the *binding energy per nucleon* in the *semi-empirical model* of *nuclei*. Surface effects become progressively more important in the model as smaller and smaller nuclei are considered. This is because medium-sized and smaller nuclei have a higher proportion of surface *nucleons,* and these have fewer neighbours and so are less strongly bound than nucleons that are completely surrounded by neighbouring nucleons. The consequent reduction in binding energy per nucleon gives a good description of the fall-off of the B/A curve for small A. [*QPM*.3]

symmetry An operation that leaves something unchanged. For example, if $f(x) = x^2$ then replacing x by $-x$ leaves the value of $f(x)$ unchanged. [*DM*.3]

symmetry energy A contribution to the *binding energy per nucleon* in the *semi-empirical model* of *nuclei*. There are actually two contributions that come under the heading of symmetry energy. One contribution is due to the *asymmetry effect*. The other contribution is due to the *Pauli exclusion principle* which in this context lowers the total energy when $Z = N$. [*QPM*.3]

synchrotron A particular kind of *cyclic accelerator* suitable for *elementary particles* that are moving at relativistic speeds. The particles are accelerated in bunches and are made to move in closed paths of large fixed radius (typically several kilometres) by a number of separate bending magnets. Since the beam consists of distinct bunches of particles, rather than a continuous beam, it is possible to adjust the frequency of the applied

accelerating fields to the speed of the particles. [*QPM*.4]

system That part of the *Universe* which is the subject of an investigation. (See also *environment*.) [*CPM*.3]

tangent The tangent to a curve at a point P is a straight line touching the curve at P, but not crossing it. The tangent to a *graph* has the same *gradient* as the graph at the point of contact. [*DM*.1]

tauon A kind of *elementary particle,* similar to an *electron*, but with a mass of 1777 MeV/c^2 (about 3477 times that of the electron). Tauons are unstable *leptons* that may occur with either positive or negative charge, the positive tauon (τ^+) being the *antiparticle* of the negative tauon (τ^-). [*QPM*.4]

tauon neutrino An elementary particle that has no known substructure and is therefore regarded as a truly fundamental particle. It is the partner to the *tauon* in the third *generation* of *leptons*. It has no charge, *spin* $\frac{1}{2}$ and a mass of less than 18 MeV/c^2. [*QPM*.4]

tauon number A dimensionless quantity that is conserved in all known interactions. The *tauon* has a tauon number of 1, and so has the *tauon neutrino*. [*QPM*.4]

telephoto lens A camera lens system used when photographing distant objects. It comprises a *converging lens* placed a small distance in front of a *diverging lens* in such a way that the *effective focal length* of this two-lens system is much greater than the distance from the front lens to the image plane. Since the image size is proportional to the equivalent focal length of the system, a reasonable degree of magnification can be achieved without the need for an excessively long lens barrel. [*DFW*.3]

telescope An optical device for enlarging the *visual angle* subtended by a very distant object, and/or increasing the apparent brightness of such objects. It uses an *objective lens* (or *objective mirror*) to gather light and produce a *real image* of the distant object in the *focal plane* of the objective. This image is viewed through an *eyepiece lens* which forms an enlarged *virtual image* of the real image at some point between the eye's *near point* (*near-point adjustment*) and *far point* (*far-point adjustment*). Telescopes that use an *objective mirror* are called *reflecting telescopes* (or just 'reflectors'), whereas those that use an *objective lens* are called *refracting telescopes* (or just 'refractors'). [*DFW*.3]

temperature An equilibrium property of *macroscopic systems*, with many overlapping shades of meaning. In macroscopic terms, temperature determines the direction of *heat flow.* When two bodies at different temperatures are brought into *thermal contact*, heat will flow from the body with the higher temperature to that with the lower temperature until the two bodies reach the same temperature. In *microscopic* terms, temperature can be related to the mean translational kinetic energy of the microscopic constituents of a system. More specifically, in the case of a *gas*, the temperature determines the distribution of *molecules* amongst their allowed *phase cells* (in *classical physics*) or *translational quantum states* (in *quantum physics*). (See *Maxwell–Boltzmann distribution* for further detail.) Assigning a value to a temperature generally involves the use of a specific *temperature scale*, such as the *absolute temperature scale*. Such scales relate temperature to some measurable property of systems such as the *pressure* of a fixed quantity of ideal gas (obtained by considering the behaviour of real gases in the limit of low pressure), or the *efficiency* of a *heat engine*. The SI unit of temperature is the kelvin (K). [*CPM*.1; *CPM*.2; *CPM*.3, *QPM*.1]

temperature scale A system for determining temperatures based on the use of an agreed unit of temperature and a number of fixed points that assign particular temperatures to reproducible physical states. (See, for example, *absolute temperature scale*.) [*CPM*.1, *CPM*.3]

tension The property of a stretched *elastic* body that tends to restore the body to its natural length. Measured in newtons, it is responsible for the *tension forces* that such a body exerts. [*PM*.1]

tension force The *force* that a stretched *elastic* body will exert on an attached object, or which one part of such a body exerts on a neighbouring part. [*PM*.1]

terminal speed The *speed* at which an object moving through a medium under the influence of an applied *force*, encounters a *resistive force* that is equal in magnitude to the applied force and therefore ceases to *accelerate*. The term is often used to refer specifically to the maximum speed that can be attained by an object falling freely through air, under the influence of *gravity* and *aerodynamic drag* alone. [*PM*.1]

tesla The *SI* unit of *magnetic field*, represented by the symbol T, and defined by the relation $1\,\mathrm{T} = 1\,\mathrm{kg\,s^{-2}\,A^{-1}}$. [*SFP*.4]

test particle An idealized *particle* that can be imagined as having such a small *mass* or *charge* that it can be introduced into a *gravitational field* or an *electric field*, for the purposes of measuring that field, without causing any significant change in the field. [*SFP.1*]

theory of general relativity See *general theory of relativity*. [*DFW*.4]

theory of special relativity See *special theory of relativity*. [*DFW*.4]

thermal conductivity A measure of a material's ability to conduct heat. The thermal conductivity κ of a material is numerically equal to the rate at which heat would flow through a slab of the material of length 1 m and cross-sectional area 1 m^2, when the temperature difference across its ends is 1 K. The units of thermal conductivity are $\mathrm{W\,m^{-1}\,K^{-1}}$. [*QPM*.2]

thermal contact The condition that exists between a *system* and its *environment* (or between two bodies) when *heat* may be exchanged between them. A system that cannot exchange heat with its environment is said to be thermally isolated. [*CPM*.3]

thermal energy A term for the sum of the kinetic energies and mutual potential energy of all the basic particles (e.g. *molecules*) in a *system.* Not to be confused with *heat*. (See *typical thermal energy of a particle*.) [*CPM*.1]

thermal equilibrium The condition of an *isolated system* in which there is no net flow of *heat* between any two parts of the system. Such a system may be characterized by a uniform *temperature*. A system is said to be in thermal equilibrium with a *heat bath* if it is

at the same *temperature* as the heat bath, since there is then no heat flow between the system and the heat bath. Thermal equilibrium represents a settled and unchanging state in which macroscopic properties are independent of time. It is also referred to as *thermodynamic equilibrium*. [*CPM*.1; *CPM*.3; *QPM*.1]

thermal isolation See *thermal contact*. [*CPM*.3]

thermal neutrons *Neutrons* that are collectively in *thermal equilibrium* with their surroundings. Inside a nuclear reactor such neutrons typically have thermal energies of about 0.08 eV. [*QPM*.3]

thermal radiation See *blackbody radiation*. [*QPM*.1]

thermal reservoir See *heat bath*. [*CPM*.3]

thermal scattering The scattering of *electrons* caused by the thermal vibrations of *lattice ions* in a *metal*. This makes a contribution to the *resistivity* of the material which increases as the temperature rises and the thermal agitation of the lattice ions increases. (See also *defect scattering*.) [*QPM*.2]

thermodynamic equilibrium See *thermal equilibrium*. [*CPM*.3]

thermodynamics The branch of *macroscopic classical physics* concerned with the study of *heat* and its relationship to energy in general. [*RU*.1; *CPM*.3]

thin-film interference The *interference* that occurs between *waves* that are reflected from the front and back surfaces of a thin film. The interference can lead to *interference fringes* or bright coloration. [*DFW*.2]

thin isothermal atmosphere A model of a planetary atmosphere in which the atmosphere is at constant *temperature* and is thin enough for any variation in gravitational acceleration to be neglected. [*CPM*.4]

thin lens A lens whose thickness is small compared with its *focal length*. [*DFW*.3]

thin lens approximation The approximation of treating a lens as though it were a *thin lens*. This is a useful approximation for many lens systems: the *lens equation* implicitly assumes the thin lens approximation, and the assumption that *all* rays pass undeviated through the *optical centre* of a lens is also only valid within the limits of this approximation. [*DFW*.3]

third law of thermodynamics A law stating that; it is impossible to reduce the *temperature* of any system to *absolute zero* by a finite number of operations. [*CPM*.3]

thought experiment An experiment that we can imagine taking place, although carrying it out may be rather difficult in practice, and for which the outcomes can be predicted based on underlying physical principles. Often used in relation to the special theory of relativity, where everyday manifestations of the phenomena predicted by the theory are rare. [*DFW*.4]

three-body problem A celebrated problem in *Newtonian mechanics* concerning the motion of three bodies (e.g. the Sun, Moon and Earth) that interact gravitationally, but are otherwise isolated. No *general solution* to this problem, for arbitrary *initial conditions*, is known. [*PM*.1]

three-dimensional A term used to describe a region of space that has three independent directions, or a body that fills such a region. [*DM*.1]

three-dimensional infinite square well A *potential (energy) well* in three-dimensional space used to model a container with rigid walls. [*QPM*.1]

tight-binding model A *quantum-mechanical model* of a *solid* that starts with the discrete *energy levels* of a large number N of isolated atoms, and then considers how each discrete level evolves into a band of very closely spaced levels as the atoms are brought together to form the *crystalline solid*. The tight binding model thus represents an approach to the *band theory of solids*. [*QPM*.2]

time constant The time constant τ of an exponential decay process is the time taken for the decaying quantity to fall to 1/e of its value at any time. Such a process is described by a function of the form $v = v_0 e^{-t/\tau}$. For a damped harmonic oscillator, of mass m, subject to a damping force that is proportional to velocity ($F_x = -bv_x$), the time constant is $\tau = 2m/b$. For an electrical circuit constructed from a *capacitor* of *capacitance* C and a *resistor* of *resistance* R the time constant is $\tau = RC$. [*PM*.2; *SFP*.3]

time-dependent Schrödinger equation The fundamental equation of *quantum mechanics* (at least in Schrödinger's wave-mechanical approach to the subject). The time-dependent Schrödinger equation is a *differential equation*. Its solution is the *time-dependent wavefunction* that provides the fullest possible description of the state of a quantum-mechanical system — including its time-evolution, in the absence of a measurement. (Measurements cause the wavefunction to change abruptly and unpredictably, in a way that is not described by the time-dependent Schrödinger equation.) [*QPI*.2]

time-dependent wavefunction A solution to the *time-dependent Schrödinger equation*. According to conventional *quantum mechanics*, the time-dependent wavefunction describing a particular *state* provides the fullest possible description of that state. [*QPI*.2]

time dilation A phenomenon arising in Einstein's *special theory of relativity*, often summed up by the statement 'moving clocks run slow'. If the time interval between two ticks of a clock is recorded as ΔT_0 in a frame in which the clock is at rest, then the time interval between the same two ticks, measured from a frame of reference in which the clock is moving at speed V, has the dilated value

$$\Delta T = \frac{\Delta T_0}{\sqrt{1 - V^2/c^2}}.$$

A consequence of this is that unstable particles observed to be travelling at speeds close to that of light, live much longer than identical particles that are observed at rest. Time dilation is built into the *Lorentz transformation*. [*DFW*.4; *QPM*.4]

time-independent Schrödinger equation For confined particles, the solutions of *Schrödinger's time-dependent equation* involve *standing waves* and it is therefore possible to write the relevant *wavefunctions* as a product of a function of space $\psi(x)$ (for one dimension) and a function of time $\phi(t)$. Thus $\Psi(x, t) = \psi(x)\phi(t)$. The functions $\psi(x)$ are themselves the solutions of a differential equation — Schrödinger's time-independent equation

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E_{tot} - E_{pot}(x))\psi = 0. \quad [QPI.2]$$

time-independent wavefunction A solution to the *time-independent Schrödinger equation*. Such solutions may be used to describe the *stationary states* of a *quantum system*. [*QPI*.2]

time of flight The interval of time between the launch of a projectile and the end of its flight. [*DM*.2]

time-of-flight mass spectrometer An instrument that measures the masses of *ions* by giving them a definite *translational energy* and measuring the time they take to cover a given distance. [*CPM*.1]

top A quantity that is conserved in *strong* and *electromagnetic interactions*, but not in *weak interactions*. [*QPM*.4]

top quark One of the six types of *quark*. It is the only quark to have non-zero *top* (or topness). [*QPM*.4]

torque A vector quantity, usually denoted by $\boldsymbol{\Gamma}$, that measures the turning effect of a force about a specified point. The torque about a point O due to a force $\boldsymbol{F}$ is given by the *vector product*

$$\boldsymbol{\Gamma} = \boldsymbol{r} \times \boldsymbol{F}$$

where $\boldsymbol{r}$ is the displacement vector from O to the point of application of $\boldsymbol{F}$. This implies that $\boldsymbol{\Gamma}$ has magnitude $rF\sin\theta$, and that it points in a direction that is perpendicular to $\boldsymbol{r}$ and $\boldsymbol{F}$, as specified by the *right-hand rule*. The *SI* unit of torque is the N m. [*PM*.4]

torque wrench A spanner-like tool for applying a specified *torque*. [*PM*.4]

total cross-section The *cross-section* due to both *elastic* and *inelastic scattering*. [*QPM*.4]

total internal reflection The phenomenon in which light, travelling in a medium of relatively high *refractive index* (e.g. glass), is reflected when it strikes an interface between that medium and a second medium of relatively low refractive index (e.g. air) at an *angle of incidence* greater than the *critical angle*. [*DFW*.2]

trajectory (a) In the context of *projectile motion*; the trajectory of a projectile is its path through space. For a projectile modelled as a *particle* that moves in the absence of *air resistance*, the trajectory is a *parabola*. [*DM*.2]

(b) In the context of *state space*; the trajectory of an evolving system is the path it traces out in *state space*. [*PM*.5]

transformer A device for transforming an *EMF* of one value to another. The operation of a transformer relies on the principle of *mutual induction* between two coils of wire with a common *magnetic flux* linkage. For 100% flux linkage, the EMFs in the two coils are related by the ratio of the number of turns on each:

$$\frac{V_2(t)}{V_1(t)} = \frac{N_2}{N_1}.$$

If the number of turns on the secondary is greater than the number of turns on the primary, the device is a step-up transformer; if the number of turns on the secondary is less than the number of turns on the primary, the device is a step-down transformer. [*DFW*.1]

transient currents The time-varying *electric currents* (usually of short duration) that build up or decay away in electrical circuits as a result of one-off events, such as the opening or closing of a switch. An example arises when a *solenoid* is connected to (or disconnected from) a source of constant *EMF*, such as a battery. Both the growth and decay of the current are described by exponential functions which take the form

$$i(t) = \left(\frac{V_{bat}}{R}\right)(1 - e^{-Rt/L})$$

for growth of current, and

$$i(t) = \left(\frac{V_{bat}}{R}\right)e^{-Rt/L}$$

for decay of current. The *time constant* for each of these processes is *L*/*R*, where *L* is the *coefficient of self-inductance* of the solenoid, and *R* is the resistance of the circuit. [*DFW*.1]

transistor A device for amplifying the power or current of an electrical signal. It usually consists of two *p–n junctions* arranged as an n–p–n or p–n–p sandwich. [*QPM*.2]

transition A process in which the state of a quantum system changes. For confined systems, this generally involves a corresponding change of *energy level*. [*QPI*.2]

translational energy See *translational kinetic energy*. [*CPM*.2]

translational energy distribution function A function $g(E)$ which, when multiplied by a small range of translational energies, ΔE, indicates the fraction $g(E)\,\Delta E$ of some specified population of particles with translational energies between E and $E + \Delta E$. The translational energy distribution function for a classical *gas* is given by the *Maxwell–Boltzmann energy distribution*. [*CPM*.1]

translational energy histogram A histogram in which the height of each bar is proportional to the fraction of particles with *translational energies* within the width of the bar. [*CPM*.2]

translational equilibrium The condition in which a system is free from any net *external force*, so that

$$\sum_i \boldsymbol{F}_i = \boldsymbol{0}.$$

The *linear momentum* of such a system will be constant. [*PM*.4]

translational kinetic energy The *kinetic energy* associated with the *translational motion* of a body. For a *particle* of mass m travelling with *speed* v, the translational kinetic energy is

$$E_{trans} = \tfrac{1}{2}mv^2.$$

For a *rigid body* of mass *M*,

$$E_{trans} = \tfrac{1}{2}Mv_{CM}^2$$

where v_{CM} is the speed of the body's *centre of mass*. In the case of a *molecule*, the translational energy is associated with motion of the centre of mass of the molecule, and does not include energy associated with

molecular vibrations or rotations (See also *relativistic translational kinetic energy*.) [*PM*.2; *CPM*.2]

translational motion A form of motion that causes every point of a rigid body to move the same distance in the same direction, and which should be contrasted with *rotational motion*. [*PM*.1]

translational quantum states The allowed quantum states of a particle moving with translational motion and confined to a container with rigid walls. [*QPM*.1]

transuranic elements Elements with *atomic number* $Z > 92$ (uranium) which are made artificially. [*QPM*.3]

transverse wave A *wave* composed of *oscillations* that take place in a direction perpendicular to the *direction of propagation* of the wave. (Contrast with *longitudinal wave*.) [*DFW*.2]

travelling wave A *wave* that propagates from one place to another. One example of such a wave is represented by the function $y(x, t) = A\sin(kx - \omega t + \phi)$. Here A is the *amplitude* of the wave, and the *phase* of the wave is $(kx - \omega t + \phi)$, where k is the *angular wavenumber*, ω is the *angular frequency*, and ϕ is the *phase constant*. [*DFW*.2]

triangle rule A graphical method of determining the *resultant* $\boldsymbol{a} + \boldsymbol{b}$ of two given vectors $\boldsymbol{a}$ and $\boldsymbol{b}$. Any *vector* can be represented graphically by an arrow, with a length that represents the *magnitude* of the vector and an orientation that represents the *direction* of the vector. To construct the arrow representing the resultant $\boldsymbol{a} + \boldsymbol{b}$, first draw an arrow to represent the vector $\boldsymbol{a}$, then, starting from the head of the arrow you have just drawn, draw a second arrow to represent the vector $\boldsymbol{b}$. The resultant $\boldsymbol{a} + \boldsymbol{b}$ will then be represented by an arrow drawn from the tail of the arrow representing $\boldsymbol{a}$ to the head of the arrow representing $\boldsymbol{b}$. The arrows representing $\boldsymbol{a}$, $\boldsymbol{b}$ and $\boldsymbol{a} + \boldsymbol{b}$ will thus form a triangle. [*DM*.2]

triatomic A term used to describe a *molecule* consisting of three *atoms* bound together by interatomic forces. [*CPM*.1]

trigonometric functions A class of *periodic functions* that includes the sine, cosine and tangent functions, as well as their inverse functions arcsin, arccos and arctan. The trigonometric functions generalize the corresponding *trigonometric ratios*, and can be defined by various means. For example, suppose a point P lies on a *unit circle* whose origin coincides with the origin of a *Cartesian coordinate system*. If a *line* from P to the origin is at an angle θ, measured anticlockwise, to the x-axis, then the x-coordinate of P determines the value of the cosine function $\cos(\theta)$ and the y-coordinate of P determines the value of the sine function $\sin(\theta)$. [*DM*.3]

trigonometric ratios Numerical quantities (the most important of which are abbreviated $\sin\theta$, $\cos\theta$ and $\tan\theta$) that are defined in terms of ratios of the side lengths of a right-angled triangle that has an interior angle θ. Given such a triangle, in which the hypotenuse (longest side) has length r, the side opposite the angle θ has length y, and the third side, adjacent to the angle θ, has length x; the three basic trigonometric ratios (formally called the sine, cosine and tangent) are defined by $\sin\theta = y/r$, $\cos\theta = x/r$, $\tan\theta = y/x$. [*DM*.2]

trigonometry The branch of mathematics concerned with the study of right-angled triangles, the associated trigonometric ratios and their generalizations. [*DM*.2]

tuned circuit An *LC* circuit that has been adjusted to a particular *natural frequency* in order to pick up external radio signals. [*DFW*.1]

tunnelling The *quantum-mechanical* phenomenon whereby a *particle* confined in a *potential well* with walls of a finite height, has a *wavefunction* that penetrates some distance into the classically forbidden region (where the particle's potential energy is more than its total energy). If this region is of a finite width, it is possible for the particle to tunnel through the classically forbidden region and be detected in some other classically allowed region where its potential energy is again less than its total energy. [*QPI*.2; *QPM*.3]

turbulence The unsteady and chaotic flow that occurs in *fluids* at *Reynolds numbers* a few thousand or greater. [*CPM*.4]

twin 'paradox' A supposed paradox arising out of the *special theory of relativity* concerning the relative ages of twins, one of whom embarks on and then returns from a long trip at a speed close to the *speed of light* to find his/her sibling much older than him/herself on return. In fact, no paradox exists and the age difference arises as a result of *time dilation* (and an effective change of *inertial frame* on the part of the traveller). [*DFW*.4]

type I superconductors Materials from which *magnetic flux* is completely excluded in the superconducting state, displaying the *Meissner effect*. Typical type I superconductors are pure metals with a long *coherence length*. [*QPM*.2]

type II superconductors Materials from which *magnetic flux* is not completely excluded in the superconducting state. Typical type II superconductors are very impure alloys or compounds with a complex polycrystalline structure. In all cases the *electrons* have a very short *coherence length*. The *high-temperature superconductors* are an extreme form of type II material. [*QPM*.2]

typical thermal energy of a particle The typical *translational kinetic energy* of a molecule in a gas in *thermal equilibrium* at temperature T. It is approximately equal to kT, where k is Boltzmann's constant. [*QPM*.1]

ultrasound Sound with a frequency above the limits of hearing of the human ear (i.e. greater than about 20 kHz). [*DFW*.2]

ultraviolet catastrophe The failure of the classical formula for the *blackbody spectrum*, which fails to show a maximum and wrongly predicts that the energy density in the blackbody spectrum tends to infinity as the wavelength decreases. [*QPI*.1]

ultraviolet radiation *Electromagnetic radiation* with *wavelength* between about 1×10^{-8} m and 4×10^{-7} m or *frequency* between about 3×10^{16} Hz and 8×10^{14} Hz. [*DFW*.2]

unbound particle A particle whose total energy E_{tot} is everywhere greater than its potential energy E_{pot}, is said to be unbound. If, in addition, E_{pot} is constant, the particle is said to be *free*. [*QPI*.2]

uni-axial rotation A term used to indicate rotation about a single fixed axis. [*PM*.4]

unification The fusing together (in a mathematical sense) of two or more theories (usually *quantum theories* of *fundamental forces*) in order to produce a more comprehensive theory that incorporates all important aspects of the original theories and usually more besides. Particular examples include the *electroweak theory* and the various proposals for *grand unified* and/or *superunified theories*. [*RU*.1]

unified field theory Any theory that attempts to unify *gravitation* and *electromagnetism* in a single *classical field theory*. The term is sometimes used to refer specifically to the unsatisfactory unified field theories formulated by Albert Einstein and various co-workers. [*RU*.1]

uniform acceleration equations See *constant acceleration equations*. [*DM*.1]

uniform circular motion A form of two-dimensional *periodic motion*, in which the *Cartesian coordinates* of a *particle* moving around the *origin* at fixed *distance* R, and with fixed *angular speed* ω, may be represented by

$$(x, y) = (R\cos(\pm\omega t + \theta_0), R\sin(\pm\omega t + \theta_0)).$$

where the + sign indicates motion in the anticlockwise sense, and θ_0 is the angular position of the particle at time $t = 0$. [*DM*.3]

uniform field A *field* that has the same value (and, in the case of a *vector field*, the same direction) at all points within some specified region of space. [*SFP*.1]

uniformly accelerated motion A form of motion in which the *acceleration* does not change with time. See *constant acceleration equations*. [*DM*.1; *DM*.2]

uniform motion A form of motion in which the *velocity* does not change with time. See *uniform motion equations*. [*DM*.1; *DM*.2]

uniform motion equations The equations that describe the *uniform motion* of a *particle*. For a particle moving in one dimension, with *initial position* x_0, the equations may be written

$$v_x = \text{constant}, \qquad s_x = v_x t.$$

In terms of *vectors*, the equations may be written

$$\boldsymbol{v} = \boldsymbol{u}, \qquad \boldsymbol{s} = \boldsymbol{u}t$$

where $\boldsymbol{s}$ represents the *displacement* from the initial *position* and $\boldsymbol{u}$ is the initial velocity. [*DM*.1; *DM*.2]

unit circle A *circle* of radius 1. Since the radius is a pure number, the unit circle is a mathematical construction rather than a physical one. [*DM*.3]

unit vector A *vector* of *magnitude* 1 that serves to indicate a specific direction. Given a displacement vector $\boldsymbol{r}$, the unit vector in the direction of $\boldsymbol{r}$ is $\hat{\boldsymbol{r}} = \boldsymbol{r}/r$. (Note that the magnitude of any unit vector is 1, *not* 1 m, nor even 1 unit.) [*PM*.1; *SFP*.1]

universal gas constant The constant

$$R = 8.314\,\text{J}\,\text{K}^{-1}\,\text{mol}^{-1}$$

that appears in the *equation of state* of an *ideal gas*: $PV = nRT$. The universal gas constant has the same value for all ideal gases, irrespective of their molecular composition. It is related to *Boltzmann's constant*, k, and *Avogadro's constant*, N_m, by $R = N_\text{m}k$. [*CPM*.1]

universal gravitational constant The constant $G = 6.673 \times 10^{-11}\,\text{N}\,\text{m}^2\,\text{kg}^{-2}$ that appears in Newton's *law of universal gravitation*. [*PM*.1; *SFP*.1]

universality The phenomenon whereby different systems may exhibit common behavioural features. [*PM*.5]

Universe A term used to describe a *system* and its *environment*. [*CPM*.3]

unpaired electron A term used to describe any *electron* that occupies a state with quantum numbers n, l, m_l and m_s in an outer *shell* of an *atom* when the state with quantum numbers n, l, m_l and $-m_s$ is unoccupied. In other words a *valence electron* that does not have a partner of opposite spin orientation in the same *subshell*. According to *Hund's rule* the outer shells contain the maximum number of unpaired electrons permitted by *Pauli's exclusion principle*. Unpaired electrons from different atoms are shared to form pairs in *covalent bonds* between atoms. [*QPM*.2]

unstable equilibrium A type of *static equilibrium* in which a system displaced slightly from its original position, has a tendency to move further away from that position. This is the kind of static equilibrium exhibited by a uniform spherical body resting at the top of a hill. [*PM*.4]

up quark One of the six types of *quark*. [*QPM*.4]

upsilon particle A kind of *elementary particle*. A *meson*, represented by the symbol Υ, consisting of a *bottom* and an antibottom *quark* ($\text{b}\overline{\text{b}}$). [*QPM*.4]

upthrust The upward force on a body that is partly or wholly immersed in a *fluid*. The existence of the upthrust is implied by *Archimedes' principle*. [*CPM*.4]

***UPT* surface** A surface representing the sets of values of *internal energy U*, *pressure P* and *temperature T* that characterize the *equilibrium states* of a given *macroscopic system* (such as a sample of matter). The surface is a pictorial representation of the system's *internal energy equation*. [*CPM*.1]

valence band The highest occupied *energy band* in a solid. In *metals* this band is only partially full and this allows the *conduction* of electricity. The valence band in an *insulator* or a *semiconductor* is completely full at very low temperatures, but *holes* are formed at higher temperatures by *electrons* being thermally excited into the *conduction band*. [*QPM*.2]

valence electrons The *electrons* in the outer shells or subshells of atoms that are responsible for chemical bonding and the conduction of electricity in metals. [*QPM*.2]

valency The number of *valence electrons* in an isolated atom of a specified element. In the context of *Drude's free-electron model* and *Pauli's quantum free-electron model*, the valency of a metal is equal to the number of electrons released per atom into the *free-electron* gas. [*QPM*.1]

valley of stability A graphical feature seen when the total energy per *nucleon* for each known *nucleus* is plotted above the corresponding point in the *Z–N plane*. The plotted points all lie very close to a surface called

the valley of stability, with the valley floor lying directly above the *path of stability* in the *Z–N* plane. [*QPM*.3]

Van Allen belts Regions surrounding the Earth where charged particles (mostly protons and electrons) are trapped by the Earth's *magnetic field*. They were discovered in 1958 by James Van Allen using data from the *Explorer* satellite mission. [*SFP*.4]

van der Waals force A weak, short range, attractive force that arises between closely separated atoms or molecules as a result of interactions between the fluctuating *electric dipoles* each of those atoms or molecules induces in the other. The van der Waals force is also known as the London force, and can be the main cause of *bonding* when stronger forces are absent, as in the cases of solid neon and solid argon, and for a range of *molecular solids*. [*QPM*.2]

vector A quantity that requires both a *magnitude* and a *direction* for its complete specification. Examples include position, displacement, velocity, acceleration, force, torque, angular velocity, momentum, angular momentum, and *electric* and *magnetic fields.* A vector can be represented by an arrow whose length is proportional to the magnitude of the vector and whose direction is the same as that of the vector. Vectors can also be specified by giving their components in a chosen coordinate system. In two dimensions, a vector $\boldsymbol{v}$ is written as $\boldsymbol{v} = (v_x, v_y)$. In three dimensions, three components are required: $\boldsymbol{v} = (v_x, v_y, v_z)$. (Contrast with *scalar.*) [*DM*.2; *SFP*.1]

vector field A quantity to which a definite *magnitude* and *direction* can be ascribed at every point throughout some region of space. Physical examples include; *electric fields*, *gravitational fields* and *magnetic fields*. [*SFP*.1]

vector product A product of two vectors $\boldsymbol{a}$ and $\boldsymbol{b}$, usually written as $\boldsymbol{a} \times \boldsymbol{b}$, and sometimes referred to as the 'cross product' of those vectors. Given two vectors $\boldsymbol{a}$ and $\boldsymbol{b}$, which are at an angle θ to each other, where $0° \leq \theta \leq 180°$, their vector product $\boldsymbol{a} \times \boldsymbol{b}$ is a vector of magnitude $ab\sin\theta$ that points in the direction perpendicular to both $\boldsymbol{a}$ and $\boldsymbol{b}$, as specified by the *right-hand rule*.

Alternatively, if the components of $\boldsymbol{a}$ and $\boldsymbol{b}$ are such that $\boldsymbol{a} = (a_x, a_y, a_z)$, and $\boldsymbol{b} = (b_x, b_y, b_z)$, then the components of the vector product $\boldsymbol{a} \times \boldsymbol{b}$ are given by

$$\boldsymbol{a} \times \boldsymbol{b} = (a_y b_z - a_z b_y,\ a_z b_x - a_x b_z,\ a_x b_y - a_y b_x).$$

[*PM*.4]

velocity The quantity that describes the (instantaneous) rate of change of the *position* of a body. For a *particle* moving in one *dimension* along the *x-axis*, the velocity v_x at any time is the rate of change of the particle's position x and is given by the gradient of the particle's *position–time graph* at the relevant time. This gradient is equal to the *derivative* of the position with respect to time, so the velocity at time t may be written

$$v_x(t) = \frac{\mathrm{d}x}{\mathrm{d}t}.$$

Velocity is a *vector* quantity, characterized by a *direction* as well as a *magnitude*. In one dimension the sign of v_x suffices to indicate the direction, but in two or three dimensions, some other method must be used to indicate direction. This is often achieved by expressing the velocity vector in terms of its *Cartesian* components, as in $\boldsymbol{v} = (v_x, v_y, v_z)$, where

$$\boldsymbol{v}(t) = \frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t}$$

and $\boldsymbol{r}(t)$ is the position vector. [*DM*.1; *DM*.2]

velocity gradient The rate of change of a component of velocity in a *fluid* in a chosen direction. [*CPM*.4]

velocity–time graph A *graph* showing how the *velocity* (usually in one dimension) of a particle depends on time. It is conventional to plot the velocity on the vertical axis and the time on the horizontal axis. The *gradient* of the velocity-time graph at any particular time is equal to the *acceleration* of the particle at that time. [*DM*.1]

velocity transformation A set of equations relating the *velocity* of a particle in one *frame of reference* to the velocity of the same particle measured in another frame of reference, which may be moving relative to the first. The velocity transformation is usually expressed in terms of the *Cartesian components* of the particle's velocity, and may be deduced from the *coordinate transformation* that relates the two frames of reference. Given a particle that moves with velocity $\boldsymbol{v} = (v_x, v_y, v_z)$ in frame of reference A, and velocity $\boldsymbol{v}' = (v'_x, v'_y, v'_z)$ in frame of reference B, then, if A and B are in *standard configuration*, with V being the speed of B with respect to A, the *Galilean coordinate transformation* implies that

$$v'_x = v_x - V,\ v'_y = v_y,\ v'_z = v_z.$$

By contrast, the *Lorentz transformation* implies that

$$v'_x = \frac{v_x - V}{1 - (Vv_x/c^2)},$$

$$v'_y = \frac{v_y\sqrt{1 - (V^2/c^2)}}{1 - (Vv_x/c^2)},$$

$$v'_z = \frac{v_z\sqrt{1 - (V^2/c^2)}}{1 - (Vv_x/c^2)}.$$

It is the Lorentz transformation that gives the correct result; the Galilean coordinate transformation only provides an approximation at speeds that are small compared with the speed of light. [*DFW*.4]

vibrational energy The *energy* associated with oscillatory motion of the parts of a system relative to the *centre of mass*. In the case of a *diatomic molecule,* the vibrational energy is associated with oscillations in the distance between the *atoms*. It does not include *translational* or *rotational* contributions to the energy. [*CPM*.2]

virtual image An image where the rays appear to diverge from the image points. Contrast with *real image*. [*DFW*.3]

virtual object The *real image* that would have been formed by *rays* converged by a lens or mirror if those rays had not been intercepted by some other lens or

mirror (for which the unformed real image acts as a virtual object). [*DFW*.3]

virtual photon A *photon* that is exchanged in a fundamental electromagnetic interaction. Such photons appear as exchange particles in *Feynman diagrams* and are not required to comply with the usual (relativistic) relationship between energy and momentum for a massless particle. [*QPM*.4]

viscosity The phenomenon of internal friction in a *fluid*, that tends to reduce the relative velocity of two neighbouring layers of the fluid and leads to energy dissipation. It also gives rise to a *viscous force* when an object moves through a fluid. (See *Stokes' law*.) Viscosity is also sometimes used as shorthand for *coefficient of viscosity*. [*PM*.1; *CPM*.4]

viscous force A *force* that tends to reduce the relative velocity of two neighbouring layers of a *fluid*. The magnitude of the force is proportional to the area of the interface between the two layers, and to the magnitude of the *velocity gradient* at the interface. [*CPM*.4]

visible light *Electromagnetic radiation* with a *wavelength* between about 4×10^{-7} m (400 nm, violet) and 7×10^{-7} m (700 nm, red) or a *frequency* between about 8×10^{14} Hz and 4×10^{14} Hz. [*DFW*.2]

visual angle The angle *subtended* at the eye by an *extended object* (or image). It is a way of expressing the object's apparent size. [*DFW*.3]

visual axis (of the eye) The axis within the eye that links the centre of the eyelens system to the *fovea*. [*DFW*.3]

vitreous humour A gelatinous material within the eye which fills the central volume of the eyeball between the eyelens and the *retina*. [*DFW*.3]

volt The *SI* unit of *electric potential* and electric *potential difference*, represented by the symbol V, where 1 V = 1 J C^{-1}. [*SFP*.2]

volume energy A contribution to the *binding energy per nucleon* in the *semi-empirical model* of *nuclei*. The volume energy is calculated by assuming that; all *nucleons* are completely surrounded by other nucleons, that each nucleon interacts only by the *strong nuclear force* with its nearest neighbours, and that all *asymmetry effects* can be neglected. (For other contributions see *Coulomb energy* and *surface energy*.) [*QPM*.3]

watt The *SI* unit of *power*, represented by the symbol W, and defined by the relation 1 W = 1 J s^{-1}. [*PM*.2]

wave A periodic disturbance that may convey energy from one point to another without any particle of the medium through which it travels being permanently displaced. Waves may be *standing* or *travelling*, solitary or continuous, and *transverse or longitudinal*. According to its type, a wave may be characterized by a *frequency* or *wavelength*, a *plane of polarization* and a *direction of propagation*. The *speed* of a (travelling) wave is jointly determined by its frequency and wavelength in accordance with the relation $v = f\lambda$. [*DFW*.2]

wavefront A line (in two dimensions) or a surface (in three dimensions) that connects points in a *wave* that have the same *phase*. [*DFW*.2]

wavefunction A solution of the *time-dependent Schrödinger equation*, usually represented by $\Psi(x, t)$ for cases involving one spatial dimension, which, according to conventional *quantum mechanics*, provides the fullest possible description of the *state* of a *quantum system*. Knowing the wavefunction that corresponds to any particular state makes it possible to predict the possible outcomes of measurements performed on the system while it is in that state and also allows the prediction of the *probability* of each of those possible outcomes. For systems that are in *stationary states* (implying that the probabilities of the possible measurement outcomes do not change with time), the wavefunction may be written as a product of functions that separately depend on space and time. The spatial part of such a product, usually represented by $\psi(x)$ in one dimension, and referred to as the *time-independent wavefunction*, then satisfies the *time-independent Schrödinger equation*. (See also *Born interpretation*.) [*QPI*.2]

wavelength The distance, measured along the direction of propagation of a wave, between successive points that are oscillating *in phase*. For convenience, wavelength is frequently thought of as the distance between two successive wave crests. [*DFW*.2]

wave mechanics The version of *quantum mechanics* developed by Erwin Schrödinger, building on de Broglie's idea of *wave–particle duality*, and giving a central role to the concept of a *wavefunction* that satisfies the *time-dependent Schrödinger equation*. [*QPI*.2]

wavenumber The reciprocal of the *wavelength* of a wave, $\sigma = 1/\lambda$. For comparison, see *angular wavenumber*. [*DFW*.2]

wave–particle duality The phenomenon whereby quantum systems (including elementary particles and electromagnetic radiation) can exhibit properties or modes of behaviour that classical physics would associate with the mutually exclusive categories of *wave* and *particle* (e.g. the diffraction of electrons). [*QPI*.1]

weak interaction See *weak nuclear force*. [*QPM*.4]

weak nuclear force A very short-range force that is responsible (among other things) for *β-decay*. It is stronger than the *gravitational interaction*, but weaker than the *electromagnetic* or *strong interactions*. It is one of the four *fundamental forces*. [*RU*.1; *QPM*.4]

weber The *SI* unit of *magnetic flux*, represented by the symbol Wb, where 1 Wb = 1 T m^2. [*DFW*.1]

weight The *gravitational force* that acts on an object as a result of its *mass*. The term is usually used in the context of objects that are close to the Earth's surface, in which case, the weight acts vertically downwards and has magnitude mg, where m is the object's mass and g is the magnitude of the *acceleration due to gravity*. [*PM*.1]

white dwarf A compact stellar object with a mass similar to that of the Sun, which, following a fuel shortage, has collapsed to a size similar to that of the Earth. Further collapse is prevented because the mutual gravitational attraction of the matter in the star is opposed by *Pauli pressure* exerted by its electrons, but the average density of the object will be very high, roughly a million times that of the Sun. [*SFP*.2]

work Any quantity of *energy* that is transferred by non-thermal means. According to one widely used convention, the symbol W is used to represent work that

is transferred *to* a system *from* its environment. This convention implies that positive values of W tend to increase the *internal energy* of the system.

The work done by a constant force $\boldsymbol{F}$ on a body that undergoes a displacement $\boldsymbol{s}$ is defined by the *scalar product*

$$W = \boldsymbol{F} \cdot \boldsymbol{s} = Fs \cos \theta .$$

If the force is not constant, then this product is replaced by the limit of an appropriate sum, which may be expressed as a *definite integral*. In the case of a force that varies in strength but always acts along the *x*-axis this integral takes the form

$$W = \int_A^B F_x \, \mathrm{d}x$$

which may be interpreted as the area under the graph of F_x against x between $x = A$ and $x = B$. In three dimensions the work done depends on the particular path (e.g. between A and B) that the body moves along and can be represented by the line integral

$$W = \int_A^B \boldsymbol{F} \cdot \mathrm{d}\boldsymbol{s} .$$

The work done on any body by a force is the energy transferred to that body by the force. When a non-zero resultant force acts on a body, the work done by that force is related to the change in the body's translational kinetic energy by the *work–energy theorem*, according to which

$$W = \Delta \mathrm{E}_{\mathrm{trans}} = \tfrac{1}{2} m v^2 - \tfrac{1}{2} m u^2$$

[*RU*.1; *PM*.2; *CPM*.1; *CPM*.3]

work done See *work*. [*PM*.2]

work function The minimum *energy* required to remove an *electron* from a *solid*. [*QPI*.1]

work–energy theorem A theorem stating that; when a single *resultant force* does work on a system, the kinetic energy of the system increases by an amount that is equal to the work done on the system. [*PM*.2]

W particle A type of *elementary particle*. A *spin* 1 *exchange particle* with a mass about 88 times that of the *proton*. There are two kinds of W particle, indicated W^+ and W^- according to charge. The existence of the W particles was predicted by the theory of the *electroweak interaction*. [*QPM*.4]

***x*-axis** A uniformly-calibrated straight line from which the *x-coordinate* of a *particle* can be read. The choice of *x*-axis incorporates a choice of origin (at which $x = 0$) and a choice of direction of increasing x. [*DM*.1]

***x*-coordinate** A quantity that describes the *position* of a point in one dimension, in a specified *coordinate system*. The *x*-coordinate of a point (e.g. the instantaneous position of a particle moving along the *x-axis*) may be positive or negative. It's magnitude indicates distance from a chosen origin, while its sign indicates a direction relative to that origin. [*DM*.1]

xi particle A kind of *elementary particle*. A *strange baryon* with *spin* ½, and a mass that is about 40% greater than that of the proton. There are two kinds of xi particle, denoted Ξ^-, Ξ^0 according to charge. Xi particles have strangeness −2, which causes them to decay in several steps; hence their alternative name — *cascade particles*. [*QPM*.4]

X-rays *Electromagnetic radiation* with *wavelength* between around 1×10^{-8} m and 1×10^{-11} m or *frequency* between about 3×10^{16} Hz and 3×10^{19} Hz. [*DFW*.2]

Young's two-slit experiment An experiment first carried out by Thomas Young in 1801, in which light from a source is *diffracted* by two closely separated narrow parallel slits and, as a result, produces a *double-slit diffraction pattern*. The experiment gives convincing evidence of the wave-like propagation of light. [*DFW*.2]

zero vector A vector that has zero *magnitude*, and therefore may be associated with any direction. It is represented in printed text by the symbol **0**. [*DM*.2]

***Z–N* plane** A plot of *atomic number Z* against *neutron number N* for *nuclei*. The *Z–N* plane may be used in various way to highlight systematic variations in the properties of nuclei. (See *path of stability* and *valley of stability* for examples.)

Z^0 particle A type of *elementary particle*. A neutral *spin* 1 *exchange particle*, with a mass about 97 times that of the *proton*. The existence of the Z^0 particle was predicted by the theory of the *electroweak interaction*. [*QPM*.4]

Printed in the United Kingdom by
The Open University